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Extraction of Geochemical Positive and Negative Anomalies Based on the Multifractal Theory and Metallogenic Prognosis

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ABSTRACT

Based on the multi-fractal theory, an algorithm to determine the minimum residual sum of squares for piecewise fitting is implemented through establishing the area - element model, according to Peruvian Don Javier porphyry copper deposit and the surrounding area surface geochemical data, and the residual sum of squares can be used as the basis to determine the number of scale-free space. The geochemical positive and negative abnormal range within the scope of the study area is delineated. By analyzing the spatial distribution of positive and negative anomalies and combined with the results of statistical analysis of the each element value, the Enrichment and Depletion Regularity of The main metallogenic elements is been Investigated. On that basis, prospecting criterions are established and it is showing that the southeast area of the ore-body is prospecting targets. The effectiveness of the method has been verified by drilling, which provides a new approach for the in-depth analysis of the geochemical data and to prospect surrounding the deposit.

Key words: multifractal, geochemistry, positive and negative anomalies, metallogenic prognosis

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INTRODUCTION

With the increasing difficulty in finding mineral resources, along with the development and penetration of modern scientific theories and technologies, the fractal theory, as a kind of nonlinear theory and a complexity theory, has shown promise for application in the fields of metallogeny and metallogenic dynamics[1,2] Many complex natural phenomena exhibit self-similarity at different scales s[3]. The fractal method describes complex objects featuring self-similarity through simple formulas with few parameters, and it has been applied to various fields including geochemistry, tectonics, extraction of remote sensing information, and processing of geophysical prospecting data [4,5].

The mineralization prospect analysis of mining areas where ores have been discovered, and surrounding areas, is very important in guiding subsequent geological work, and new theories and methods are needed in the analysis of chemical prospecting data and information gathering in mining areas and surrounding areas [6]. During the exploration process in many areas, drillholes are often drilled in the area surrounding the expected ore bodies, and a judgment that no ore deposit is present will be made, and drilling stopped, if no ores are obtained from these drillholes. However, many vein-shaped, lenticular, or deep ore bodies are easily missed due to insufficient grid density or drillhole depth. Therefore, effectively decomposing the complex geochemical fields, and extracting anomalous geochemical fields with prospecting significance, is a key step to deciding on the effectiveness of geochemical prospecting for ore deposits in a given area[7].

A metallogenic process involves the enrichment and dilution of geochemical elements at different stages. Both dilution and enrichment are vital geochemical phenomena during the metallogenic process[8] , and they are reflected by negative and positive anomalies, respectively, in anomaly diagrams. Studies have shown that the multifractal method can rationally describe such a metallogenic process and enrichment laws, and the multifractal theory is believed to represent a more universal distribution pattern of geochemical elements. The content-area (C-A) multifractal model proposed by Cheng Mingqiu et al. is a powerful tool for fractal filtering in multiple spaces, and decomposition of the complicated geochemical background and superimposed anomalies[9] . Using the surficial protogenetic sample data from the Don Javier porphyry copper mining area in southern Peru as an example, this study employs the multifractal theory to determine the threshold values of positive and negative anomalies to delineate the enrichment and dilution ranges of geochemical elements. In addition, the structural characteristics of the distributions of elements in the study area are analyzed to direct the prospecting in the area surrounding the ore deposit. Finally, a verification test performed by drilling holes in the study area confirms that the proposed method can achieve an ideal metallogenic prognosis.

1 Geology of the Study Area

Don Javier porphyry copper mine is located in the Arequipa in southern Peru. It lies in the Incapuquio fault zone of the Andean orogenic belt, with favorable metallogenic conditions(Fig.1). The famous Cerro Verde is only 17 kilometers northwest of the study area. In the study area, the outcrops mainly include lower Jurassic volcanics, lower-middle Jurassic limestones, upper Jurassic to lower Cretaceous sandstones, Pliocene volcanics, Holocene alluvial deposits, and slope-wash deposits. Affected by the subduction of the Nazca plate and the Inca fracture, a dome structure is formed due to the development of a NW-trending fault and the invasion of the Yarabamba rock mass, which is the main ore-controlling structure. The study area is extensively developed with intermediate-acid magmatic rocks, which are mainly diorite and granodiorite. There are at least two phases of granite porphyry intrusion. The main ore body is NW trending with south and east lateral prostration. The host rocks are porphyry, diorite, and various types of breccia. The mine area has experienced multi-phase hydrothermal activities, and as a result propylitization, silicification, and beresitization are extensively developed, with universal presence of massive pyritization. The ores here are mainly mineralized sulfides, with a common combination of chalcopyrite-pyrite-molybdenite [10].

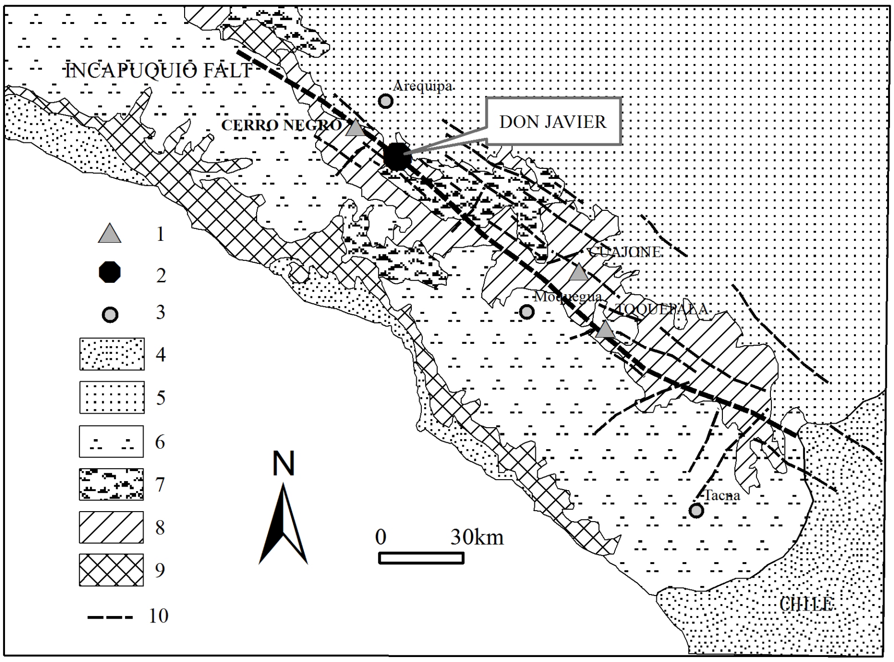


Fig.1 Location and regional geological map of research area（after geological map of Peru on the scale of 1/1000000）

1-neighboring cobre deposite;2-research area;3-major city;4- Neogene and Quaternary sediments;5-Upper-Tertiary high cordillera continental sediments etc.; 6-post-ore volcanics and Mis-Tertiary continental sediments; 7-Cretaceous-Paleogene pre Cordillera voleano-plutonic terrane;8-Jurassic-Cretaceous marine sedments; 9-pre-Cambrian basement and Mesozoic coastal range.

2 Multifractal analysis and the Model

2.1 Fractal Theory

Multifractal analysis (i.e. multi-scale fractal analysis) can characterize the self-similarity of different geological characteristics and modes. With reference to the C-A model established by Cheng Qiuming et al. [9], the multifractal model adopted in this study can be simply mathematically described as follows:

$$A(c) = Kc^{-D} \quad x > 0 \qquad \textbf{\textit{Expression 1}}$$

where c stands for the element content (density c), and K >0 is the proportional constant; $A(c)$ stands for the regional area (or perimeter, area, frequency, etc.) of the element content greater than a threshold value; and D stands for the fractal dimension, which is adopted in the fractal theory to describe the nonuniformity of the enrichment and dilution of chemical elements as multiple scale spaces, so as to quantitatively describe the complexity degree of the change of elements under the corresponding different geological actions.

A linear model described as follows with one variable was obtained by taking the logarithms of both sides of the above formula.

$$\ln[A(c)] = -\lambda \ln c + \ln(K) \qquad \textbf{\textit{Expression 2}}$$

2.2 Establishment of the Model

The common models of the multifractal theory for extracting the geochemical anomalies are content-perimeter, content-area, content-distance, content-frequency, etc. [11]. The C-A method was adopted in the present study to establish the model.

(1) The isolated points and blank sampling areas were removed to determine the range of the study area. Subsequently, the inverse distance weighting (IDW) was adopted for interpolation to obtain the grid data containing element values.
(2) In the C-A method, the area (A) with a content value greater than a specific given value is calculated using the range confined by the generated contour lines. In this study, the grid data obtained from interpolation was utilized directly for the area statistics. The two methods are theoretically the same, and both of them can be realized easily.
(3) The logarithmic values of element contents (lnC) were divided into groups with the step length taken as 0.2. The obtained element content-area data were plotted on double-logarithmic axes to obtain the scatter diagram.
(4) The two demarcation points, chosen from the double-logarithmic coordinates by the least squares method, were divided into three segments for fitting. The dividing points were determined based on the condition that the residual sum of squares (E) was minimized, so as to improve the objectivity and veracity of the fitting.

$$E = E_1 + E_2 + E_3 = \sum_{i=1}^{m} [\ln A(c_i) + D_1 \ln c_i - \ln(K_1)]^2$$
$$+ \sum_{i=m+1}^{n} [(\ln A(c_i) + D_2 \ln c_i - \ln(K_2)]^2 + \qquad \textbf{\textit{Expression 3}}$$
$$\sum_{i=n+1}^{\mathrm{end}} [(\ln A(c_i) + D_3 \ln c_i - \ln(K_3)]^2$$

where E stands for the residual sum of squares; m stands for the number of the scattered point of the first demarcation point; n stands for the number of the scattered point of the second demarcation point and $m<n$; and D_1, D_2, and D_3 correspond to the fractal dimensions of three scale-free spaces. After obtaining the C-A double-logarithmic scatter diagram, the approximate range of the demarcation points was selected artificially, and the residual sums of squares for different values of m and n within their ranges were further calculated to choose the minimum value ($E_{\min}$) so as to determine the optimal demarcation points for fitting.

(5) After fitting, the obtained element values c_1 and c_2, which correspond to the point of intersection between the first and second lines and that between the second and third lines from left to right, respectively, were the upper limit of the negative anomaly and the lower limit of the positive anomaly. The corresponding slopes D_1, D_2, and D_3 respectively correspond to the fractal dimensions in the divided three scale-free spaces.

3 Model Establishment and Analysis

3.1 Statistical Characteristics of the Sample Data

Based on the surficial sample data, four primary metallic elements – Cu, Ag, Mo, and As – were chosen for analysis. The statistical results show that the primary metallic elements in the mining area show obvious peaks (Table 1). Regarding skewness, the elements are all of positive deviation with Mo having the greatest deviation.

Table 1 Descriptive statistics of elements content

Element	NumValid	Interval/ ($\times10^{-6}$)	Mean/ ($\times10^{-6}$)	StdDev	Skewness	Kurtosis	C.V
Cu	1527.00	[0.038,14400]	425.91	911.48	6.68	71.51	2.14
Mo	1519.00	[0.4,2570]	17.56	74.79	27.00	894.30	4.26
Ag	1527.00	[0.01,67.8]	1.57	4.51	8.20	89.59	2.88
As	1472.00	[1,1150]	45.22	66.64	6.15	68.79	1.47

The main metallogenic element Cu has the greatest variance within the mining area, but its skewness, kurtosis, and coefficient of variation (CV) are relatively small. The average value varies considerably among the different elements. CV was used to effectively eliminate the interference of average value differences in the comparison of the variation between different elements. The comprehensive data comparison revealed that the elements are all nonuniformly distributed and their CVs are all greater than 0.2. Among them, Mo is the most nonuniform, followed by Ag and Cu as the second and third.

3.2 Establishment of a C-A Model

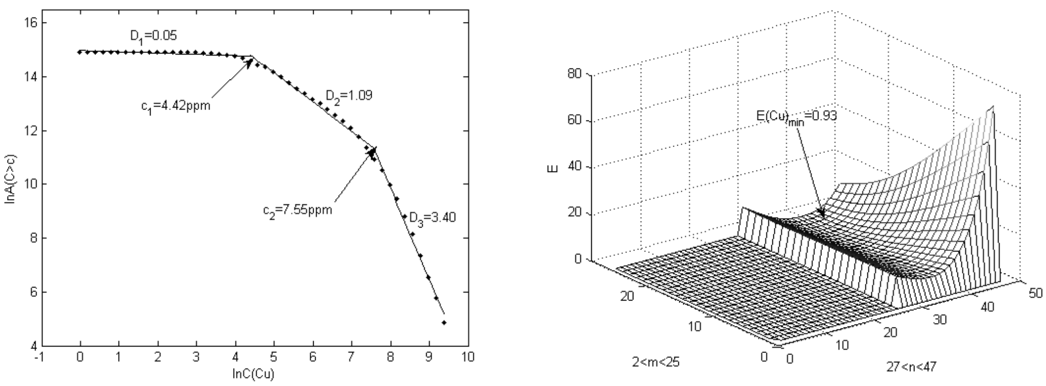
The multi-element test results for the four primary metallic elements, namely Cu, Ag, Mo, and As, from 1,515 protogenetic rock samples in the study area, were used to establish the models. Different residual sums of squares (E) were acquired from the fitting of different values of the demarcation points m and n. The values of m and n that resulted in the lowest value of E were used. The fitting diagram of the elements, and the 3D diagram of value E, are shown in Fig. 2.

3.3 Evaluation of the Model and Geological Analysis

1) The accuracy of the linear piecewise fitting in the modeling process has always been a key factor that influences the precision of the model. In this study, the area was calculated based on the grid data obtained from interpolation, and the range of demarcation points was selected manually. The final demarcation points were determined by a program calculating the minimum residual sum of squares E_{min}. Finally, the fitting was conducted. It can be seen from Fig. 2 that the fitting is highly satisfactory.

Table 2 Model parameters

Element	Manual intervention conditions	E_{min}	D_1	D_2	D_3	c_1（ppm）	c_2（ppm）
Cu	2<m<25,27<n<48	0.93	0.05	1.09	3.40	4.42	7.55
Mo	2<m<22,25<n<40	1.95	0.12	1.56	4.26	6.57	133.55
Ag	2<m<14,16<n<43	3.47	0.04	1.19	3.56	0.69	9.05
As	2<m<30,32<n<47	0.37	0.03	0.93	3.59	15.33	75.94



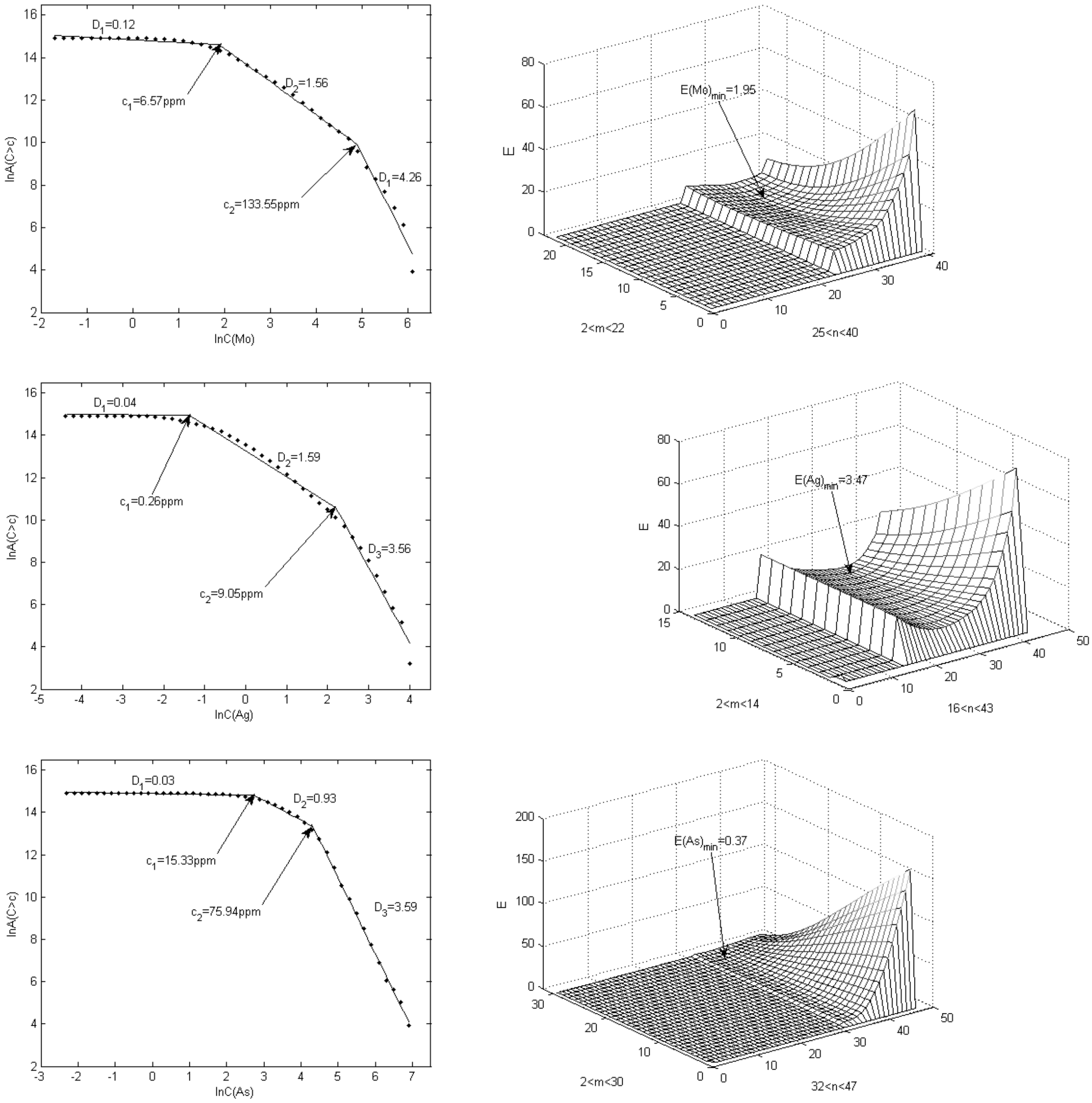


Fig.2 lnA(C>c)-lnc log-log plot and residual sum of squares three- dimensional map of of different elements

As shown in Fig. 2 and Table 2, the fitting effect becomes worse as the residual sum of squares (E) increases. When the value of E is too large, the number of segments for fitting is no longer suitable and it should be increased. Therefore, the value of E can be regarded as a basis for determining the number of scale-free spaces. If E is too large, the fitting is unsuitable and the number of segments should be increased, i.e. the number of scale-free spaces should be increased, which also means that the metallogenic geological process is more complex.

(2) According to the results of the residual sum of squares and the fitting effect, the four primary metallic elements in the study area can be divided into three scale-free spaces. The first scale-free space corresponds to the dilution area of the elements and it presents negative anomalies. The second scale-free space corresponds to the normal range. However, we cannot rule out the possibility that this space might have experienced several periods of element enrichment and dilution, resulting in the element content values returning to the normal range. The third scale-free space corresponds to the enrichment area of the elements and it presents positive anomalies. The fractal dimension D quantitatively describes the degree of uniformity of spatial distribution of the geochemical elements. In general, the smaller D is, the more clustered the elements are and the more nonuniform the distribution is[12]. The fractal dimension D of Mo was greater than that of the other elements in the study, indicating that Mo was the most nonuniformly distributed element, with Cu and Ag ranked second and third. This result is consistent with that derived from the analysis of CV.

(3) The morphological characteristics of the multifractal curves represent the complexity of the geological process to some extent. Cu, Mo, and Ag had similar multifractal curves, indicating similar causes of formation among them. As had a narrow second scale space, suggesting that As had strong enrichment and dilution.

4 Analysis of Anomalies and Metallogenic Prognosis

As mentioned above, the upper limits of positive anomalies and the lower limits of negative anomalies for the elements in the study area were determined according to the fitting results and the anomaly diagram shown in Fig. 3. Through analyzing and comparing the positive and negative anomalous distributions of the four elements in a known mineralization range, the surrounding potential metallogenic ranges were identified to provide guidance for further prospecting.

(1) In the Cu anomaly diagram, the range encircled by positive anomalies was an approximate rectangle and the distribution range of drillholes with ores discovered was roughly located within the area encircled by positive anomalies. The distribution of negative anomalies in the area showed a small patchy pattern. The northwestern part of the mineralization range had wide negative anomalies and the poor mineralization in this area was confirmed through deep drillholes. The northern anomalies were confirmed as mineralization anomalies, and the two positive anomalies in the southern part indicate promising mineralization prospects, which should be the first-choice target regions for future prospecting work in the area.

(2) According to the linear correlation analysis of Mo and Cu, these two elements were not strongly correlated, but their positive distributions in the ore body were identical. In addition, along the NW-SE direction, their positive anomalies were distributed in a beaded pattern, and their negative anomalies were distributed along both sides of the line of positive anomalies in a scattered patchy pattern and formed an area with similar width to the known ore body. The distribution range of positive anomalies decreased from northwest to southeast, which coincided with the NW trend and south and east lateral prostration of the ore body. Positive anomalies extended towards the southeast, indicating that the known southeastern mineralization range had a more promising mineralization prospect.

(3) Ag is a co-existing mineralization element in the study area and it is closely associated with Cu mineralization [10]. The positive anomalies of Ag were located at the southeast part of the known ore body with no positive ranges encircled by the mineralization zone, indicating that the southeastern direction of the ore body might have a more promising mineralization prospect.

(4) As is the main harmful element of copper mines, and it showed a large encircled distribution range of positive anomalies using the multifractal method. However, within the mineralization range, NE-SW-trending positive anomalies were symmetrically distributed with NE-SW-trending negative anomalies, and the positive and negative anomalies along the southeastern direction showed a scattered patchy distribution pattern, indicating strong enrichment and dilution. This result also suggests a promising prospect of deep mineralization.

(5) The zoning of the primary halo elements of a deposit refers to the phenomenon that the anomalies of different chemical elements present a regular spatial distribution under a certain geological process. Studies on the laws of element zoning are helpful for evaluating the known ore body, and can provide theoretical guidance for the exploration of deep and blind ore bodies[13-15]. The enrichment of Mo and Ag in the study area showed the zoning pattern with a southeastern trend, which is consistent with the extension direction of the ore body. The enrichment of Cu, Mo, and Ag was low in the southern area. For the positive and negative anomalies extracted using the multifractal method, negative anomalies and the normal range were often presented irregularly in a scattered patchy pattern in the range, with dense distribution of positive anomalies. This indicates that the cause of mineralization also led to the obvious enrichment and dilution of local elements, accompanied with good mineralization, which can be an indicator for further ore prospecting.

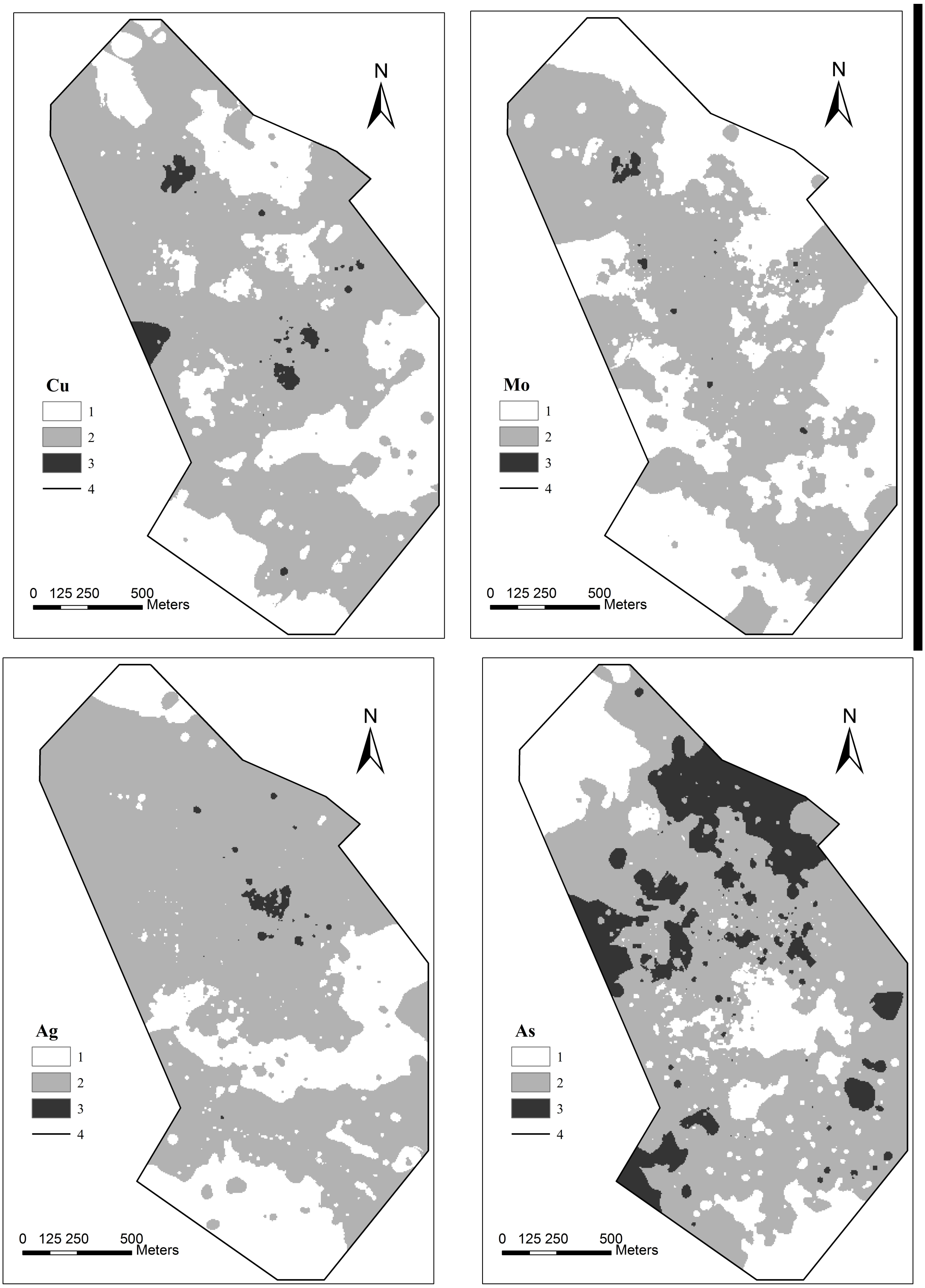


Fig.3 Positive and negative anomalies map of different elements
1-negative anomaly;2-normal area;3-positive anomaly;4-boundary of the study area

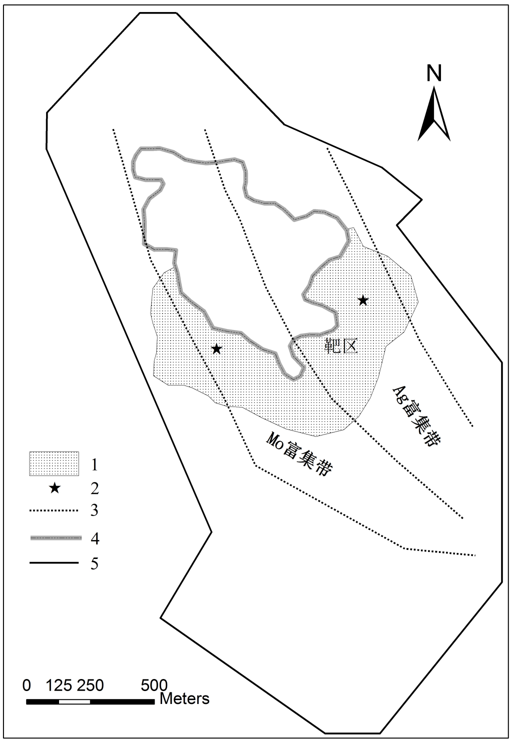


Fig.4 Metallogenic prediction map of research area

1- target range;2- mineralization drilling;3- enrichment zone boundary;4- known mineralization range;5- boundary of the study area

To sum up, the SW part of the known mineralization range, namely along the trend of the known ore body, is more promising for ore prospecting. Hence, the southern part of the study area was encircled as the prospecting target region (Fig. 4). During the verification test, conducted by drilling, industrial ore bodies were found in the southern region, while no ores were found in the drillholes arranged in the northern region outside the target region.

CONCLUSION

(1) Because the geochemical fields formed by the enrichment and dilution of elements had different spatial characteristics, the multifractal method can be used to effectively distinguish the dilution area, normal area and enrichment area. The method that uses the area-element model, and determines the demarcation points by minimizing the residual sum of squares, is highly precise, with satisfactory fitting and a significant denoising effect. In addition, by using this method the positive and negative anomalous (enrichment and dilution) ranges of elements can be encircled at the same time. By analyzing the characteristics and different combinations of the distributions of positive and negative anomalies, the mineralization mechanism can be more thoroughly interpreted to identify target regions for further prospecting.

(2) The multifractal curves of the elements in the study area had similar characteristics, suggesting that these elements formed under similar conditions. The results derived from analyses of CV and the fractal dimension *D* were consistent, indicating that Mo is the most nonuniformly distributed, followed by Ag and Cu as the second and third, and As having relatively strong enrichment and dilution.

(3) According to the distribution of positive and negative anomalies in the study area, the primary co-existing elements Mo and Ag show a remarkable zoning pattern at the NW-SE direction.

(4) The areas where positive and negative anomalies are distributed in a scattered patchy pattern have strong mineralization activities, which can be considered an indicator for further ore prospecting in the study area. The first-choice target regions for prospecting identified by the proposed method were further confirmed by drilling holes in these areas, proving that this method can serve as a satisfactory tool for metallogenic prognosis.

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