

Article

Geochemical Quantitative Assessment of Mineral Resource Potential in the Da Hinggan Mountains in Inner Mongolia, China

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Abstract: Studying surface geochemical anomalies is important for detecting the presence of mineral deposits. However, distinguishing inconspicuous geochemical anomalies is a challenge for geochemists. This paper studies geochemical quantitative prediction for Pb–Zn metallic mineral deposits by identifying inconspicuous surface geochemical anomalies mainly associated with the Permian and Jurassic strata in the middle-southern Da Hinggan Mountains metallogenic belt. Some new methods are employed to highlight weak surface geochemical anomalies. The weak surface geochemical anomalies of Pb and Zn are effectively highlighted by the average contrast values of Pb–Zn–Ag–Cd. The similarity coefficient with the large typical discovered deposits is used to identify new Pb–Zn mineralized anomalies and delineate new prospecting target areas. The denudation degree of mineral deposit is determined by the ratio of $(W \times Sn)/(As \times Sb)$. The analogy method and areal productivity method are employed for resource prediction. Thirty-six prediction areas with Pb–Zn resources of 307.73 million tons are delineated. Five prediction areas are verified, and some new mineral deposits are proven by drilling. The verification results show that the predicted resources are very reasonable and credible. This paper is a successful case of quantitative prediction assessment of mineral resource potential, which can be used as a reference for future prospecting activities.

Keywords: geochemical anomaly; contrast value; similarity coefficient; quantitative assessment; the Da Hinggan Mountains metallogenic belt

1. Introduction

With the development of the economy, the demand of human society for mineral resources is increasing. Moreover, a large number of surface mines and shallow buried mines have been found and exhausted. Mineral prospecting work has faced severe challenges [1–4], and it now has to be conducted in thick covered areas or some unknown areas [5–7]. Therefore, the difficulty of mineral prospecting is gradually increasing. How to improve the efficiency and ability of scientific mineral prospecting is increasingly being investigated by government departments and related scholars. The prediction of mineral resource potential, which can avoid and reduce exploration risks and improve exploration

efficiency, has become an important means to deal with such challenges and has important research and practical significance [8–15].

China's National Geochemical Mapping Project (Regional Geochemical–National Reconnaissance, RGNR project) initiated in 1979, has now covered more than six million square kilometers of China's territory. Substantial geochemical data containing prospecting information have been obtained, with great contributions to China's mineral exploration and geological work [16,17].

However, a great many of the previous studies focused on the screening and verification of geochemical anomalies with high concentration, multiple elements, and large size [18–20]. With the deepening of mineral prospecting, it can be generally found that the geochemical anomalies in mineralized bodies with large buried depth are very weak with low concentration and small-sized; hence, they are always ignored [21–25]. Therefore, it is of great significance to (a) summarize previous research and regional geochemical data of China, (b) identify the missed geochemical anomalies mentioned above, (c) establish geochemical models of metallogenic indicator elements for typical deposits, (d) explore the geochemical distribution of elements and its relationship with regional metallogeny and metallogenic potential, and (e) evaluate the potential for mineral resources. These studies can provide a scientific basis for the deployment of resource exploration work, for the discovery of new mineral resources, and to address the supply-and-demand situation of mineral resources.

The Da Hinggan Mountains metallogenic belt is one of the 19 important metallogenic zones in China [26]. New mineral deposits were frequently found in recent years in the middle-southern section of the Da Hinggan Mountains metallogenic belt. Therefore, it has gained more and more attention from many scholars, and it has been delineated by the China Geological Survey as a key prospecting area for Pb–Zn polymetallic mineral deposits [27–31]. Because of depletion of the previously proven deposits, there is a growing need to explore new deposits. Studying surface geochemical anomalies is important for detecting mineral deposits, but distinguishing inconspicuous geochemical anomalies poses a greater challenge for exploration geochemists. Therefore, this paper studies geological–geochemical prospecting information and quantitative prediction for Pb–Zn polymetallic mineral deposits in the middle-southern Da Hinggan Mountains metallogenic belt. This study reports the results from the geochemical quantitative prediction leading to the identification of some new Pb–Zn metallic deposits, located in the Da Hinggan Mountains metallogenic belt of China. This study could be a turning point for mineral exploration strategy in the metallogenic belts of China, especially for Pb–Zn metallic deposits.

2. Description of the Study Area

2.1. Geological Setting

The research area is located in the Inner Mongolia Autonomous Region of China, with Hebei to the south, Heilongjiang, Jilin, and Liaoning to the east, and Inner Mongolia to the north. The study area belongs to the southern part of the Da Hinggan Mountains in the late Paleozoic accretive orogenic belt, the southern part of the Da Hinggan Mountains volcanic belt, and the eastern and western sides of the deep fault of the main ridge of the Da Hinggan Mountains (Figure 1).

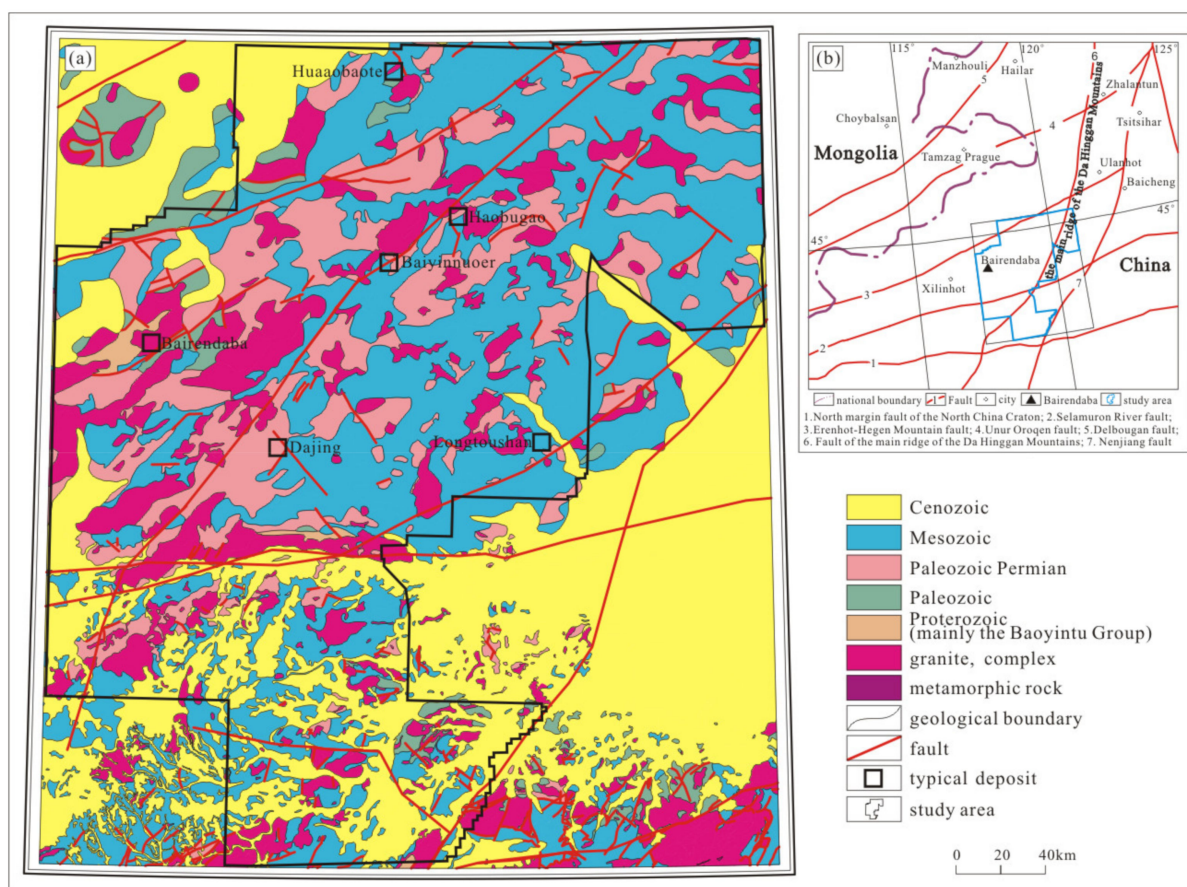


Figure 1. The geological (a) and geotectonic (b) map of the study area [32–37].

The rocks exposed in the region belong to the Paleoproterozoic Baoyintu Group and the Paleozoic and Cenozoic strata. The Baoyintu Group is a set of sedimentary rocks undergoing low greenschist phase transition with small amount of metamorphic volcanic rocks [32]. The Paleozoic strata are mainly Silurian and Permian. The Silurian is a set of clastic rocks, sandstone, limestone, slate, and foliated rhyolitic rocks of neritic facies [33]. The Permian, a shallow micrometamorphic volcanic–sedimentary rock system, is composed of volcanic lava, tuff, feldspar quartz sandstone, hard sandstone, slate, local sandwich-crystal tuff, limestone, and clastic arenas [34]. The Carboniferous system is mainly formed by carbonatite, and it partly contains sodium volcanic rocks. The Cenozoic strata mainly constitute the Quaternary system.

In the study area, tectonic activities are intense, and faults and folds are well developed. The trends of the main tectonic lines are NNE, and the faults control the formation of tectonic mountains and tectonic basins in the region. The most developed structures are NE-trending faults, while NW-trending faults are also developed, revealing multi-period activities. The regional faults are mainly the deep faults of Selamuron River, Erenhot–Hegen mountain, the main ridge of the Da Hinggan Mountains, and Nenjiang. The Erenhot–Hegen Mountain and Selamuron River faults are sutural. South of the Selamuron River fault belongs to the accretion zone of the continental margin of North China Craton. The Erenhot–Hegen Mountain fault is the boundary between the northern and southern sections of the Da Hinggan Mountains Orogenic belt in late Paleozoic Erathem. The study area is located in the semiarid middle- and low-mountain landscape area. Streams are developed, and stream sediments are easy to be collected [35–37].

Mesozoic neutral–acidic magmatic activity is frequent and intense in the Da Hinggan Mountains metallogenic belt, which forms the famous Da Hinggan Mountains magmatic belt [38–42].

The intrusive rocks are well developed and widely distributed, and the overall distribution is in the NNE direction, which is consistent with the regional tectonic line [43]. The rock types are simple, mainly neutral–acidic intrusive rocks, with a small number of slightly alkaline intrusions [44]. They are composed mainly of granite of the Jurassic and the Early Cretaceous Epoch and diorite of the Permian.

The volcanic rocks are mainly produced in the Mesozoic strata, and the Paleozoic volcanic rocks are produced in the early Permian Dashizhai Formation [45]. The Paleozoic volcanic rocks are mainly neutral–acidic volcanic rocks and some acidic rocks. The Mesozoic volcanic rocks are dominated by acidic volcanic rocks, followed by neutral–acidic volcanic rocks, with eruptive facies. The Cenozoic volcanic rocks are dominated by basalt.

The Permian strata in this region generally underwent regional dynamic thermal metamorphism and formed increasing metamorphism from low-greenschist facies to high-greenschist facies to low-amphibolite facies [37]. The metamorphic strength weakened from the bottom to the top, and the low-greenschist facies rock assemblage was formed in the upper Permian.

2.2. Regional Mineral Characteristics

The study area is rich in mineral resources, and it is an important source of Cu, Pb, Zn, and Sn with a host of deposits; it has been divided into three subzones of the metallogenic belt. From west to east, they are the Pb–Zn–Ag–Cu metallogenic subzone, the Sn–Pb–Zn–Fe–Cu metallogenic subzone, and the Cu metallogenic subzone [46].

Several large-scale Ag–Pb–Zn polymetallic mineral deposits were found in the middle–southern section of the Da Hinggan Mountains metallogenic belt [47], such as the Bairendaba Ag–Pb–Zn polymetallic mineral deposit [36,48], the Baiyinnuoer Pb–Zn–Ag deposit [37,49], the Haobugao Pb–Zn–Cu–Sn deposit [50], the Dajing Cu–Sn–Pb–Zn–Ag polymetallic mineral deposit [51], the Longtoushan Pb–Zn deposit [52], and the Huaoabaote Pb–Zn–Ag polymetallic mineral deposit [53,54]. These mineral deposits are proven, independent, representative, and regarded as typical deposits in this belt [55,56].

More than 80% of the Ag–Cu–Pb–Zn polymetallic deposits are found in the Permian Dashizhai and Huanggangliang Formations [57]. Lead isotope tracer showed that most of the metallogenic materials of Pb and Zn in the study area come from the Permian, while some of them come from the Paleoproterozoic Baoyintu Group [28,37].

The NE-, E–W-, and NW-trending fault structures control the spatial distribution of magmatic rocks, mineral deposits and orebodies in this area. In general, the mineral deposits in this study area are zonal distribution in the NE and NW directions.

Mesozoic neutral–acidic magmatic activities were intensive, accounting for more than 50% of the area. Magmatic activities provide abundant material sources and thermodynamic conditions for the formation of mineral deposits and are the main controlling factor for the space–time structure of mineral deposits [58].

Most of the mineral deposits in the area are located in the inner and outer contact zones of volcanic–intrusive composite plutons [59]. Among them, Cu, Ag (Pb, Zn) mineral deposits are concentrated around the neutral–acidic rock, whereas Sn (Cu, Pb, Zn) polymetallic mineral deposits are mainly distributed in acidic rock and its surroundings. Alkaline granite is closely related to rare earth mineralization [15].

3. Materials and Methods

3.1. Materials

Geochemical data from stream sediment survey in the Da Hinggan Mountains metallogenic belt carried out by China Geological Survey in the RGNR project were used for delineating surface geochemical anomalies, and we identified the weak geochemical anomalies and delineated new prediction areas for ore prospecting in this paper.

The geological reports, geochemical reports, grade analysis reports of the ore body, reserves calculation and verification reports, soil data, and drilling data of the proven large

ore deposits were used to summarize the geological–geochemical prospecting models of the typical ore deposits.

Drilling data and reserves reports of the newfound ore deposits were used to verify the accuracy and reliability of quantitative assessment results.

3.2. Methods

3.2.1. Data Analysis and Quality

Stream sediment samples were collected at a density of one sample per km² in an area about 75,000 km². Equal weight of samples in 4 km² were combined into a composite sample for analysis of 39 elements or oxides: Ag, As, Au, B, Ba, Be, Bi, Cd, Co, Cr, Cu, F, Hg, La, Li, Mn, Mo, Nb, Ni, P, Pb, Sb, Sn, Sr, Th, Ti, U, V, W, Y, Zn, Zr, SiO₂, Al₂O₃, K₂O, Na₂O, CaO, MgO, and Fe₂O₃ [60–62]. In this paper, the analytical data for 18,807 stream sediment samples were used.

The analytical procedures followed those in the RGNR guidelines [63]. Certified reference materials (CRMs) developed by IGGE [64–66], equal to about 8% of the total samples, were inserted randomly into each batch of 50 samples and analyzed along with field samples [7,67–70]. The relative error (RE%) to monitor the between-batch bias and the percent relative standard deviation (RSD%) to assess the analytical precision were then calculated as follows:

$$RE (\%) = (C_d - C_r) / C_r \times 100, \quad (1)$$

$$RSD (\%) = \frac{\sqrt{[\sum_{i=1}^n (C_d - C_r)^2] / n}}{C_r}, \quad (2)$$

where C_d is the determined concentration, and C_r is the certified reference concentration.

The analyses were considered acceptable if the absolute values of RE were $\leq 50\%$ for samples with concentrations within three times the detection limit and $\leq 35\%$ for samples with concentrations more than three times the detection limit. If the absolute REs fell outside these limits, the batch samples were reanalyzed.

The analyses were considered acceptable if the RSDs were $\leq 40\%$ for samples with concentrations within three times the detection limits and $\leq 25\%$ for samples with concentrations more than three times the detection limits.

Duplicate samples (equal to 5% of the total number of samples) were randomly inserted to evaluate the precision of the analyses. The percent relative deviation (RD%) was calculated as follows:

$$RD(\%) = [(C_1 - C_2) / ((C_1 + C_2) / 2)] \times 100, \quad (3)$$

where C_1 is the first determination, and C_2 is the second determination. Analyses were considered acceptable if the absolute RDs were $\leq 40\%$. All elements in all duplicates showed reliable precision.

The analysis of soil and rock samples from the typical ore deposits followed the analytical procedures above-mentioned.

3.2.2. Data Processing

A normal distribution test was conducted on raw data of each element. If the raw data followed the normal or lognormal distribution, the mean and standard deviation (S dev) of raw data were calculated. The threshold value for each element was defined as the mean value plus two standard deviations. If the raw data did not conform to the normal or lognormal distribution, the extreme outliers exceeding three times the standard deviations were removed from the geochemical data iteratively until all the remaining data fell within the range of the three standard deviations and met an approximate normal distribution. A new dataset composed of the remaining data was obtained. The mean values, as the background values of elements, were calculated using the remaining data [70].

The threshold value of each element used in this paper was defined as the background value plus two standard deviations. The contour maps for the elements were prepared using the kriging method available in Surfer 8.0 (Golden Software Inc., Golden, CO, USA).

3.2.3. Weak Geochemical Anomalies Extraction

The contrast value of an element is the ratio of its geochemical anomaly concentration to its background value. The contrast values of elements can be used to indicate the intensity and clarity of geochemical anomalies, and they are commonly used to delineate the anomalies and identify the weak anomalies [22,23,71]. In this study, the contrast values of elements were employed to identify and highlight the weak geochemical anomalies.

3.2.4. Selection of Element Combinations of the Typical Deposits

Six deposits (mainly large mineral deposits) were selected as typical deposits: the Bairendaba and Huaobaote hydrothermal vein Ag–Pb–Zn deposits in the western slope, the Baiyinnuoer skarn type Zn–Pb–Ag(–Sn) deposit, the Haobugao skarn type Pb–Zn–Cu–Sn deposit, and the Dajing hydrothermal vein Sn–Cu–Pb–Zn–Ag deposit in the main ridge, and the Longtoushan hydrothermal Ag–Pb–Zn deposit in the east slope of the central southern section of the Da Hinggan Mountains metallogenic belt. The typical deposits' metallogenic geological environment, orebody characteristics, and geochemical anomaly characteristics were studied in detail in order to establish their geological–geochemical prospecting models as a reference for mineral prediction.

The indicator element combination characteristics of the typical deposits were distinguished as standard samples for mineral prediction. To reduce the influence of some extra high values on the assignment process and to strive for a reasonable assignment, the average concentrations of each element in the inner zone of geochemical anomalies of the typical mineral deposits were adopted. On the basis of the background values of element concentration in different stratum and magmatic rocks in the region, the geochemical anomaly threshold value of each element was determined, and one, two, and four times the threshold were taken as the outer, middle, and inner zones of geochemical anomalies. The average concentrations of elements in the inner zone of geochemical anomalies of the typical deposits were employed as the indicator element combinations in this study.

3.2.5. Similarity Coefficient Calculation

The similarity coefficient between each data point and the abovementioned standard sample (the major indicator element combinations of the typical deposit) was calculated as follows:

$$D_{(Si)} = \sqrt{\frac{\sum_{k=1}^p [lg(X_{sk}) - lg(X_{ik})]^2}{m}}, \quad (4)$$

where s is the standard sample (each typical deposit), i is the observed sample to be judged (each data point), m is the number of elements of the element association, X_{sk} is the concentration value of the k -th element of the standard sample, X_{ik} is the concentration value of the k -th element of the observed sample, and $D_{(Si)}$ is the numerical distance between the observed sample and the standard sample.

The similarity coefficient can be obtained by the transformation of the above formula as follows:

$$R = 1 - D_{(Si)}/\text{Max}(D), \quad (5)$$

where $\text{Max}(D)$ is the maximum value of $D_{(Si)}$, and R is the similarity coefficient.

Finally, the similarity coefficients of all observation samples and standard samples are between 0 and 1, in which the observation points where the typical mineral deposits were located had a similarity degree of 1 with themselves, while the others were all less than 1. A closer R to 1 indicated the observed sample was closer to the standard sample.

3.2.6. Mineral Resource Prediction

In this study, the similarity coefficient between each stream sediment sampling site and typical deposits were calculated for prediction and evaluation of the prediction area.

The geochemical quantitative estimation of mineral resources was based on the geological–geochemical parameters of the six typical deposits. The areas close to the geological and geochemical characteristics of the typical deposits and with high similarity coefficients were considered favorable areas for mineralization and preferentially selected as the prediction areas. The reserves of the typical deposits were used to estimate the quantity of resource in the newly predicted favorable areas.

3.2.7. Estimation of the Degree of Denudation

The degree of denudation is one of the important parameters in the evaluation and prediction of mineral resource potential [72]. In this paper, the horizontal zoning of the elements was used to estimate the denudation degree of deposits. It has been indicated that the stream sediment distribution rules of zonality–evaluation values (i.e., the ratios between the linear productivities of front- and rear-halo elements) or the multiplicative (or additive) index (i.e., the ratios between multiplicative or additive values of the element contrast values of front- and rear-halo or indicator elements) in different parts of the orebodies serve as indicators of the degree of denudation [20]. After several such tests, the degree of denudation was determined by the ratio of $(W \times Sn)/(As \times Sb)$ in this study.

3.2.8. Methods for Resource Prediction

Two geochemical methods were used for resource prediction in this paper: the analogy method (hereinafter referred to as P_{r1}) and the areal productivity method (hereinafter referred to as P_{r2}).

The core idea of the analogy method is that the resources of the deposit are in direct proportion to the anomaly size of elements in the stream sediments. The anomaly size means the product of the abnormal area and average concentration of Pb and Zn. The core idea of areal productivity method is that the resources in the region are proportional to the areal productivity of the anomaly area. The resources of Pb and Zn (hereinafter referred to as PR), anomaly dimension (AD), and areal productivity (AP) of the six typical deposits are listed in Table 1.

Table 1. The resources of Pb and Zn, anomaly dimension, areal productivity of the six typical deposits.

Typical Deposit	Resources ($\times 104$ Tons)	AD	AP
Bairendaba	132.56	9516.51	8507.1
Huaaobaote	42.82	6439.69	5747.28
Haobugao	63.26	4143.2	3306.71
Baiyinnuoer	123.06	2831.09	2281.82
Dajing	50	2378.83	1934.45
Longtoushan	53.12	4713.7	4451.98

The calculation formula of the analogical method is as follows:

$$SC \times \frac{AP}{P} = \frac{AP_r}{P_{r1}} \quad (6)$$

After the transformation, it becomes as follows:

$$P_{r1} = \frac{AP_r}{AP} \times \frac{1 - w_r}{1 - w} \times \frac{1}{SC} \times P, \quad (7)$$

where AP is the product of the area and the average concentration of elements in the typical deposit, P is the resource of the typical deposit, AP_r is the product of the area and the average concentrations of elements in the metallogenic prediction area, P_{r1} is the resource

of the metallogenic prediction area, w is the denudation coefficient of the typical deposit, w_r is the denudation coefficient of the metallogenic prediction area, and SC is the similarity coefficient between the metallogenic prediction area and the typical deposit.

The formula of the areal productivity method is calculated as follows:

$$SC \times \frac{S(X - B)}{\frac{P}{1-w}} = \frac{S_r(X_r - B_r)}{\frac{P_{r2}}{1-w_r}}. \quad (8)$$

After the transformation, it becomes as follows:

$$P_{r2} = \frac{S_r(X_r - B_r)}{S(X - B)} \times \frac{1 - w_r}{1 - w} \times \frac{1}{SC} \times P, \quad (9)$$

where S is the area of the typical deposit, P is the resource of the typical deposit, X are the average concentrations of elements in the typical deposit area, B is the element background in the typical deposit area, S_r is the area of the metallogenic prediction area, P_{r2} is the resource of the metallogenic prediction area, X_r are the average concentrations of elements in the metallogenic prediction area, B_r is the element background in the metallogenic prediction area, w is the denudation coefficient of the typical deposit, w_r is the denudation coefficient of the metallogenic prediction area, and SC is the similarity coefficient between the metallogenic prediction area and the typical deposit.

4. Results

4.1. Weak Anomaly Extraction

Geochemical contour maps were drawn by using the contrast values of Pb–Zn ore deposit indicator elements. Cumulative frequency classification was adopted for the contour map, with frequency as 25%, 50%, 80%, 90%, 95%, and 98%. Compared with the geochemical map of Pb, the average contrast values of Pb–Zn–Ag–Cd could highlight the known deposits more obviously, especially the Pb–Zn–Ag metallic deposits. In addition, it highlighted many low and weak geochemical anomalies. This can provide new clues for mineral exploration in the areas with weak and low surface geochemical anomalies (Figure 2).

4.2. Element Combinations Characteristics of the Typical Deposits

The average concentrations of elements in the inner zone of geochemical anomaly of the typical deposits employed as the indicator element combinations in this study are listed in Table 2.

4.3. The Contour Map of the Similarity Coefficient

The mapping method of the similarity coefficient contour map was similar to that of the contrast value geochemical map. The cumulative frequency was adopted for classification in the similarity coefficient contour map, and it was divided into seven levels as follows: 50%, 80%, 90%, 95%, 97%, and 99%. If the cumulative frequency of the similarity coefficient reaches 99%, it indicates that 1% of the observed samples are similar to the standard samples and have prospecting potential. If the cumulative frequency of the similarity coefficient reaches 97%, it indicates that 3% of the observed samples are similar to the standard samples and have a certain mineralization rate.

Figure 3 is the contour map of the similarity coefficients of the Baiyinnuoer Pb–Zn deposit as the standard sample. It shows that the observation samples similar to the Baiyinnuoer Pb–Zn deposit were mainly concentrated in the southern middle ridge of the Da Hinggan Mountains metallogenic belt. It also clearly outlines the scope of the middle ridge of the Da Hinggan Mountains, refines the map content, and delineates some new geochemical anomalies referenced for further research.

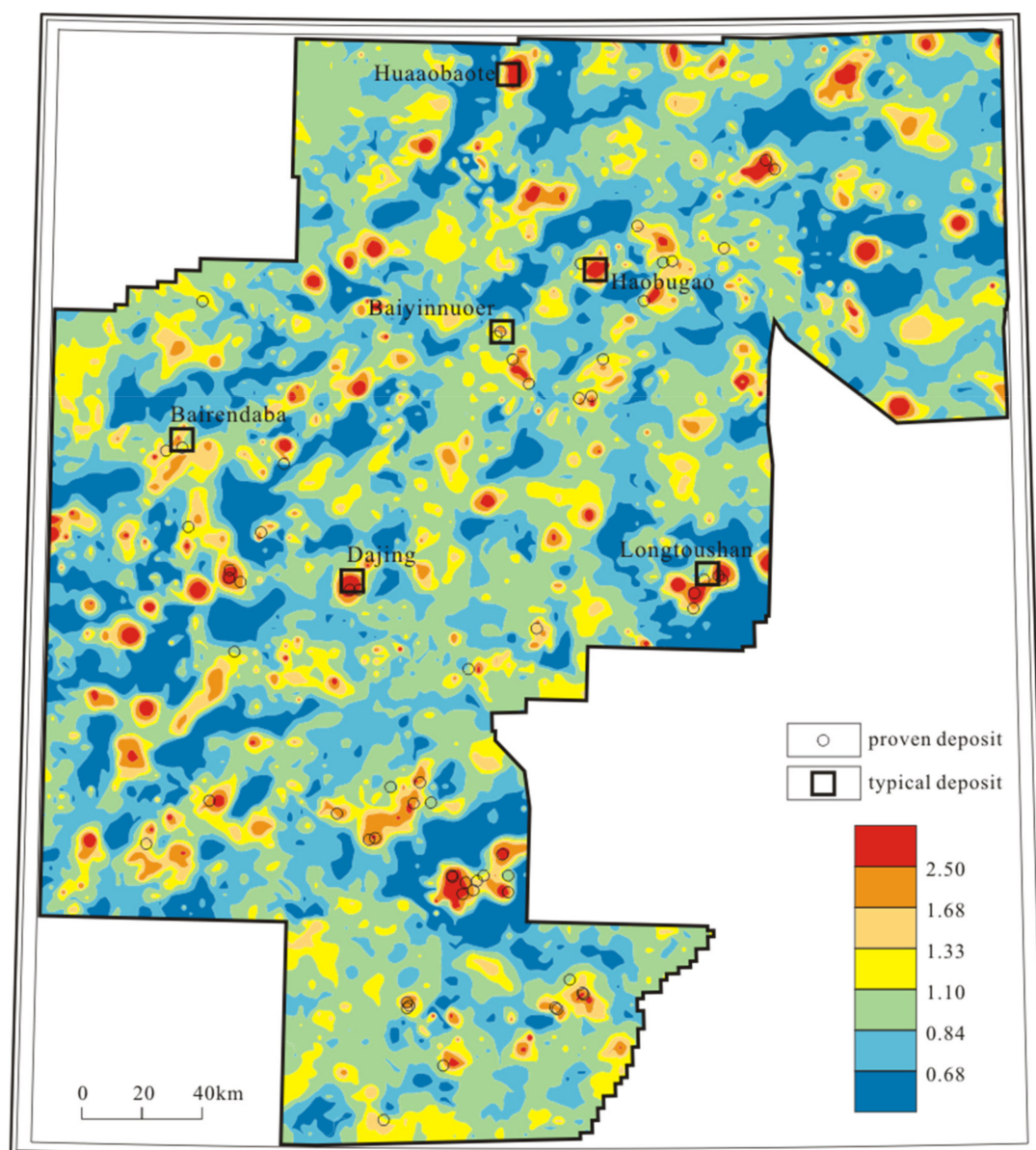


Figure 2. Geochemical contour map of the average contrast values of Pb-Zn-Ag-Cd.

Table 2. The average concentrations of major indicator elements in the inner zone of geochemical anomaly of the typical deposits.

Name of Deposit	Indicator Element Combination (the Mean Value of the Inner Zones of Geochemical Anomalies). The Concentration of Elements Is 10^{-6} g/g; That of Ag and Cd Is 10^{-9} g/g.
Bairendaba	Ag(784.00) + Bi(8.58) + Cd(283.80) + Mo(7.07) + Sb(50.19) + Zn(249.38)
Huaaobaote	Ag(2263.13) + As(313.36) + Cd(971.10) + Mo(6.22) + Sb(26.17) + W(33.42) + Zn(500.96)
Haobugao	Ag(1416.80) + As(486.82) + Bi(2.88) + Cd(9507.90) + Cu(66.07) + Pb(245.44) + Sb(8.28) + Sn(41.98) + W(9.24) + Zn(1191.31)
Baiyinnuoer	As(265.70) + Bi(3.17) + Cd(330.50) + Pb(44.42) + Sn(25.10)
Dajing	Ag(1506.50) + As(210.94) + Cd(1014.00) + Pb(644.03) + Sb(4.45) + Zn(83.97)
Longtoushan	Ag(4005.00) + As(609.35) + Bi(43.86) + Cd(713.77) + Mo(300.90) + Pb(560.47) + Sb(17.92) + Zn(2517.98)

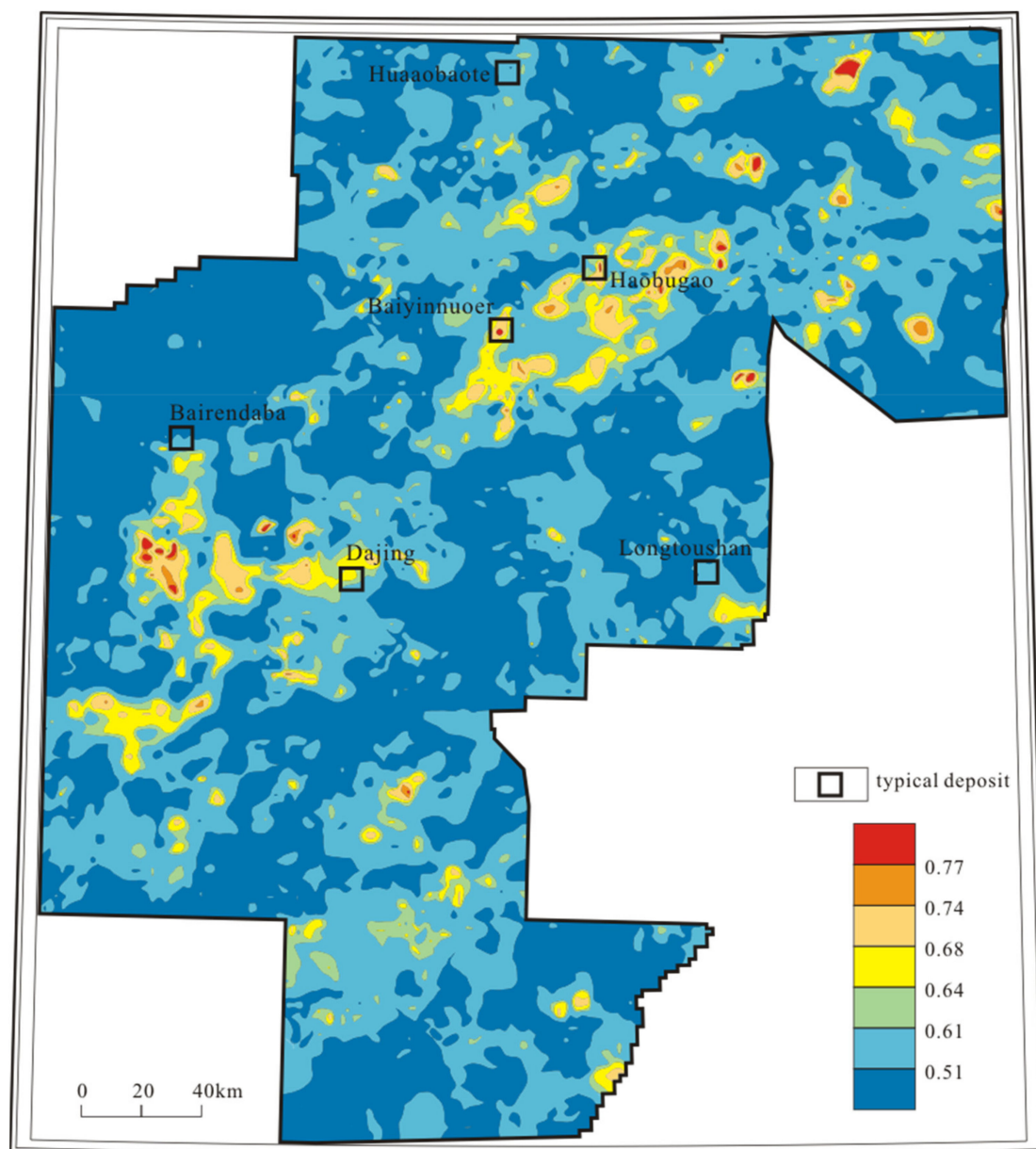


Figure 3. The contour map of the similarity coefficients with the Baiyinnuoer Pb–Zn deposit.

4.4. Metallogenic Prediction Area Delineation

4.4.1. The Criteria of the Metallogenic Prediction Area Delineation

On the basis of the comprehensive research of geological, mineral, geophysical, remote sensing data, the geochemical map, the geochemical anomaly map, the contrast value contour map, the contour map of denudation degree, the similarity coefficient contour map, and the typical mineral-prospecting models, the metallogenic prediction areas were optimized as follows:

Parameter 1: The similarity of element association between the observation sample and a typical deposit is large, and the cumulative frequency grading is equal or greater than 97%.

Parameter 2: The metallogenic geological conditions are favorable. The main ore-bearing strata in this study area are the Permian and Jurassic strata, where most of the Pb–Zn polymetallic deposits can be found. In addition, the favorable area for mineralization is one where the geological structure and magmatic rocks are well developed.

Parameter 3: There are discovered mineral deposits or mineralization points nearby.

Parameter 4: The contrast value of Pb or Zn is equal to or greater than 1.3 (cumulative frequency grading $\geq 90\%$).

Parameter 5: The average contrast value of Pb–Zn–Ag–Cd is equal to or greater than 1.3 (cumulative frequency grading $\geq 90\%$).

Parameter 6: There are at least three elements in Pb, Zn, Ag, and Cd whose contrast value is not lower than 1.1 (cumulative frequency grading $\geq 80\%$).

The prediction areas were divided into two subareas: A-level and B-level prediction areas. If the predicting area met all the parameters listed above, it was classified as an A-level prediction area. If the predicting area met the parameters listed above except for parameter 3, it was classified as a B-level prediction area.

4.4.2. The Result of the Metallogenic Prediction Area Delineation

According to the criteria of the metallogenic prediction area delineation, 36 predicting areas were delineated in the study area, including three A-level prediction areas and 33 B-level prediction areas (Figure 4).

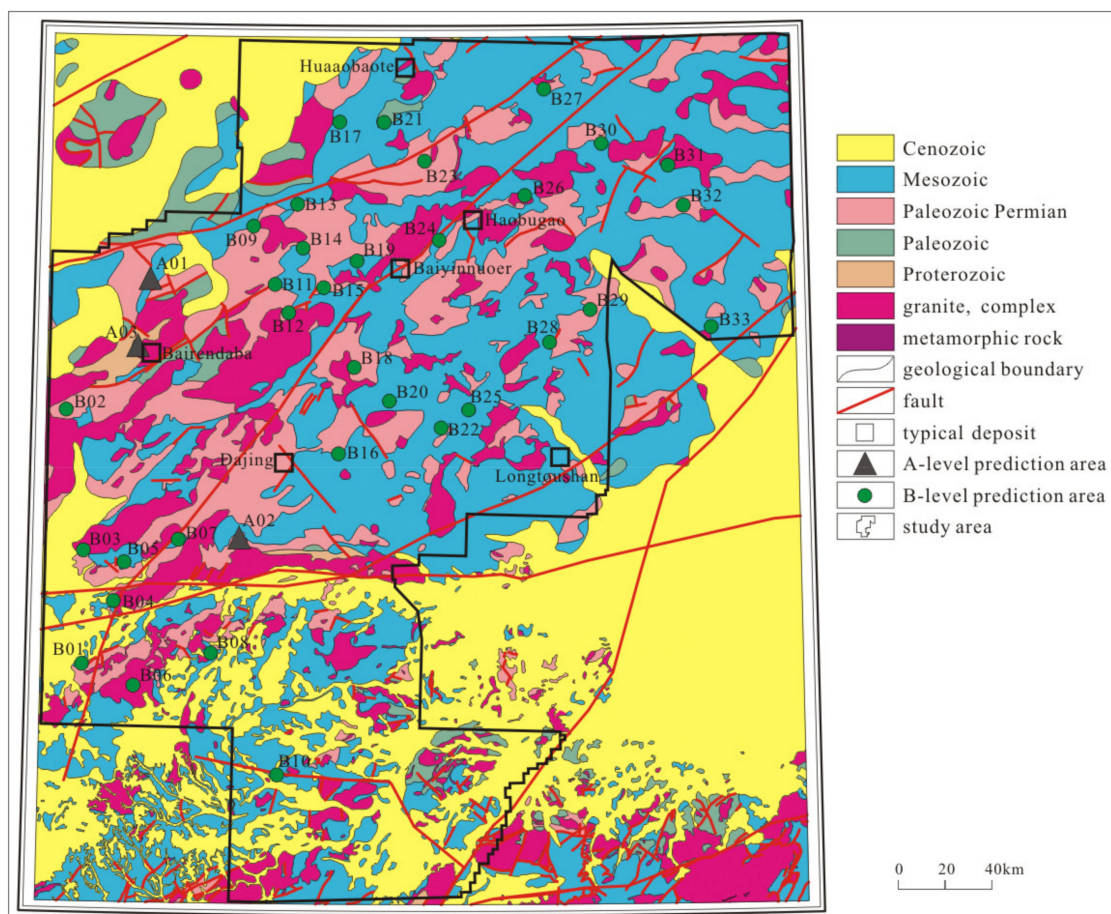


Figure 4. Distribution diagram of the metallogenic prediction areas.

What needs illustration is that predicted areas consistent with the known deposits were not included in the 36 predicted areas. If the prediction areas were similar to more than one typical deposit in the six standard samples at the same time, the typical deposit with a closer spatial distance and a closer geological condition was selected as the best similar typical deposit for subsequent resource estimation.

4.5. Estimation Results of Denudation Degree

The ratio of $(W \times Sn)/(As \times Sb)$ indicated that the Huaobaote Pb–Zn ore deposit, Bairendaba Pb–Zn ore deposit, and Longtoushan Pb–Zn ore deposit showed a low degree of denudation. The Baiyinnuoer Pb–Zn ore deposit, Haobugao Pb–Zn ore deposit, and Dajing Sn–Pb–Zn–Ag ore deposit showed a middling degree of denudation (Figure 5).

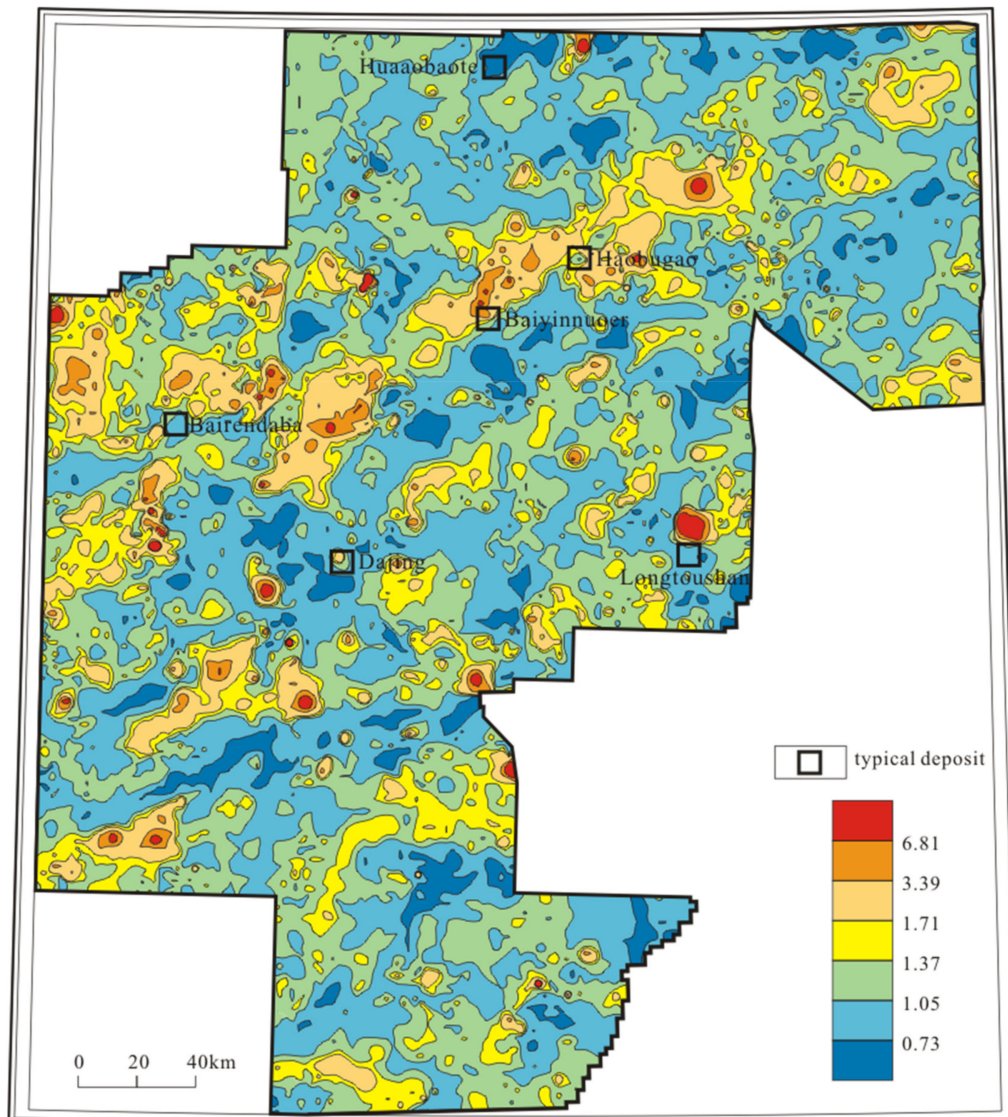


Figure 5. The contour map of the ratio of $(W \times Sn)/(As \times Sb)$.

4.6. Resources Prediction Results

A comparison showed that the resource calculation results of the two methods were relatively close to each other. The arithmetic weighted mean of predicted resources (PRs) from the two methods was adopted in this paper.

The final predicted resources (PRs) were calculated as follows:

$$PR = 0.6P_{r1} + 0.4P_{r2}. \quad (10)$$

The result shows that the resources of the three A-level prediction areas and 33 B-level prediction areas were 52,500 tons and 3.2 million tons, respectively (Table 3).

Table 3. The predicted resources of the prediction areas ($\times 10^4$ tons).

Number	P _{r1}	P _{r2}	PR
A01	0.94	0.58	0.8
A02	4.01	2.76	3.51
A03	1.05	0.78	0.94
B01	9.36	7.71	8.7
B02	9.54	7.13	8.58
B03	5.83	4.13	5.15
B04	20.69	16.23	18.9
B05	25.51	25.92	25.67
B06	28.11	19.85	24.8
B07	9.67	6.6	8.44
B08	3.61	2.47	3.15
B09	21.17	17.47	19.69
B10	2.2	1.61	1.96
B11	9.06	6.24	7.93
B12	17.98	17.26	17.69
B13	24.83	22.84	24.03
B14	5.6	3.78	4.88
B15	11.38	7.85	9.97
B16	5.26	3.59	4.59
B17	3.8	3.27	3.59
B18	5.68	3.53	4.82
B19	3.89	2.66	3.4
B20	9.83	8.52	9.31
B21	3.56	2.26	3.04
B22	1.52	0.93	1.28
B23	22.26	19.2	21.04
B24	15.89	10.95	13.91
B25	1.73	1.16	1.5
B26	12.9	9.75	11.64
B27	1.47	0.92	1.25
B28	1.83	1.73	1.79
B29	10.83	1.94	7.27
B30	10.24	8.26	9.45
B31	5.19	3.77	4.62
B32	7.19	6.23	6.81
B33	3.99	3.09	3.63

4.7. Verification of the Prediction Areas and Reliability Analysis for the Prediction Resources

There were five prediction areas verified. Prediction area B02 was verified by the 10th Institute of Geology and Mineral Exploration of Inner Mongolia and the Beijing Institute of Geology for Mineral Resources. It was identified as a Pb–Zn–Ag metallic mineralization point by drilling, but a reserve report has not been published.

Prediction area B24 was verified by the 10th Institute of Geology and Mineral Exploration of Inner Mongolia and the Haihan Minerals Limited of Chifeng City, and a new Pb–Zn metallic ore was found. The new Pb–Zn metallic ore body, with a length of 200 m and a width of 1.03–3.10 m, is controlled by drilling. The spatial extension direction, prongness, and dip angle of the ore body are 40°, southeast, and 64°–66°, respectively. The contents of Pb and Zn are 2.15% and 2.32%, respectively.

The reserves of three prediction areas, B23, B29, and B33, have been reported.

The prediction area named B23 is located in the Shabuleng Mountain of the West Ujimqin in Inner Mongolia. Drilling data display 16 ore bodies with a length of 50–447 m and a width of 1.10–10.19 m. The spatial extension direction of the ore bodies is 40°–335°. The reserves of Zn are 101,700 tons.

Prediction area B29 is located in the Habutegai of Alukeerqin in Chifeng City in Inner Mongolia. Drilling data show that two ore bodies with a length of 100–200 m

have been found. The reserves of Pb, Zn, and Ag are 39,257 tons, 26,399 tons, and 17.26 tons, respectively.

Prediction area B33 is located in the Laodaogou of Zhalute Banner in Tongliao City in Inner Mongolia. The reported reserves of Pb, Zn, and Ag are 8978.7 tons, 6226.8 tons, and 3.77 tons, respectively.

The proven resources (P) and the predicted resources of the three prediction areas mentioned above are compared in Table 4. The results show that the predicted resources are greater than the proven resources. The proportion of the proven resources in the predicted resources of the three different deposits are different, which may be related to their exploration degree, indicating that the predicted resources are credible.

Table 4. Comparison table of the predicted and proved resources ($\times 10^4$ tons).

Number	P _{r1}	P _{r2}	PR	P
B23	22.26	19.2	21.04	10.17
B29	10.83	1.94	7.27	6.57
B33	3.99	3.09	3.63	1.52

5. Conclusions

Surface geochemical anomalies from stream sediment survey, including weak geochemical anomalies, contain a lot of prospecting information. Weak geochemical anomalies should be given enough attention for further study. The weak surface geochemical information of Pb, Zn can be highlighted by the average contrast values of Pb–Zn–Ag–Cd.

The similarity coefficients with large typical proven deposits can be used to identify new Pb–Zn mineralized anomalies and delineate new prospecting target areas.

The denudation degree of the proven ore deposits can also be determined by the ratio of $(W \times Sn)/(As \times Sb)$ for stream sediment data.

Thirty-six prediction areas with Pb–Zn resources of 307.73 million tons were delineated, and some new ore deposits were found by drilling verification.

This paper reports a successful case of quantitative prediction assessment of mineral resource potential by geochemical methods, which can be used as a reference for future prospecting activities.

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