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Three-Dimensional Prediction and Evaluation of Baiyanghe Uranium Deposit in the Xuemistan Volcanic Belt, Xinjiang

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Abstract: Taking the Baiyanghe uranium deposit in Xinjiang as an example, the authors used the 3D geologic modeling and analysis software SKUA-GOCAD to establish a 3D geologic model of its topography, structure, stratum, granite, and ore body based on the study and knowledge of the geologic background, characteristics, and metallogenic rules of the deposit. Meanwhile, the authors summarized the 3D prediction model, conducted a quantitative extraction and analysis of favorable metallogenic information, and carried out the 3D prediction and study on the Baiyanghe uranium deposit by combining the 3D weights of the evidence method and the 3D informational method. Based on the analysis and prediction results, the deep prospecting target area was delineated. The 3D metallogenic prediction of the uranium deposit was achieved, which has provided technical support for the exploration of the Baiyanghe uranium deposit and a beneficial reference for the 3D metallogenic prediction of other minerals. Such a practice can provide a certain practical application value and a reference value for the research in this field.

Keywords: Baiyanghe uranium deposit; 3D geologic model; 3D quantitative prediction; weights of evidence method; informational method

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1. Introduction

A mineral forecast refers to a method and technology that apply metallogenic theory, analyze metallogenic elements by studying metallogenic rules, summarizes prediction elements by combining geophysical and geochemical detection information, judge prospective areas by analogy prediction, provide guidance on exploration, and discover deposits [1]. Although the concept of 3D geologic modeling was first proposed in 1993 [2], Haldorson (1984) was involved in the 3D modeling of oil reservoir dynamic simulations [3]. In 1989 and 1992, Mallet published two articles on the "discrete smooth interpolation" modeling method [4,5], which marked a breakthrough in geological surface technology in three-dimensional structural technology. Research on 3D geological modeling in China began in the late 1980s with the introduction of EarthVision software. Subsequently, many scholars at home and abroad have made several theories and methods of 3D geological modeling technology and the development of 3D geological modeling software in different fields, and have put forward many targeted methods for describing 3D underground space [6]. With the rapid development of 3D computer technology, standing progress has been made in geologic prediction methods. In 1957, Allais studied the number of deposits and achieved results [7]. The study of statistical analysis methods for geological research proceeded to the phase of mineral resource evaluation. In 1969, Harris' multiple discriminant analysis laid the theoretical foundation for the evaluation of mineral resources [8]. Agterberg proposed the weight method of the evidence resource evaluation in 1990 [9]. The quantitative prediction and evaluation technology of mineral resources has evolved from a 2D to a more intuitive and visualized 3D prediction methodology. Based on the many years of achievements and experience of the 2D geologic survey and the reliance on the solid 3D geologic model enabled by 3D visualization technology, the 3D quantitative prediction theory of mineral resources aims to achieve the positioning and evaluation of deep mineral resources through quantitative delineation and the selection of a favorable combination of metallogenic factors [10]. Based on the digital deposit model and under the guidance of the geological prospecting model, this method makes a 3D prediction of hidden ore through the cube prediction model, which can supplement and deepen existing research results and provide an important reference for future prospecting [11]. Exploration in the Baiyanghe uranium-beryllium deposit started in the 1950s, and relatively abundant geological data have been accumulated. Since 2006, with a new round of uranium polymetallic ore prospecting, a large number of basic geologic, geophysical, and geochemical data have been obtained. In particular, in this study extensive geophysical and geochemical prospecting was conducted, which will provide basic data for 3D prediction and evaluation of the Baiyanghe mining area and its perimeter.

The research on the Baiyanghe deposit has always been in a two-dimensional state, and the underground geological conditions have not been shown in three dimensions, which leads to an unclear local understanding. With the new round of prospecting breakthrough, the Baiyanghe Deposit needs to submit new target areas and increase its resources. On this basis, this research work came into being.

2. Geological Background of the Study Area

The Baiyanghe uranium–beryllium deposit is an important volcanic deposit in the western Xuemistan volcanic belt in Junggar, Xinjiang. The ore bodies are all developed in Yangzhuang granite, with a minimum thickness of 0.43 m, a maximum thickness of 12.35 m and an average of 3.20 m, with a variation coefficient of 88%, and the thickness of ore bodies varies greatly. The average grade of a single sample of ore body is 0.1635%, and the variation coefficient is 132%. The grade of single ore segment is 0.0806–0.6591%, the average grade is 0.1490%, and the variation coefficient is 67.02%. The ore body grade changes slightly and locally. The average grade of industrial ore bodies (metal quantity/ore quantity) is 0.1247%; The minimum thickness of uranium ore body is 0.50 m, the maximum thickness is 8.60 m, the average thickness is 3.21 m, the variation coefficient is 85.7%, and the thickness of ore body changes greatly. The average grade of a single sample of ore body is 0.248%, and the variation coefficient is 162.7%, which indicates that the grade of ore body changes greatly. The average grade (metal quantity/ore quantity) of industrial ore bodies in the deposit is 0.205%. Based on the existing geological information on the ore body and the analysis of favorable metallogenic factors, the model range of the study area was determined (Figure 1), with the north–south coordinate ranging from 5,156,902 to 5,161,000, the east–west coordinate ranging from 562,893 to 575,000, and the elevation is 1006.1–1444.08 m (coordinate system type: right angle of projection plane; Ellipsoid parameter: Beijing 54 ellipsoid; Projection type: Gauss–Kruger projection).

The geological bodies of the Baiyanghe deposit include three categories: volcanic rocks, granite, and vein rock (Figure 1).

The main strata exposed in the study area are the Silurian Xiemisitai Fm (S1-4x), Upper Devonian Hongguleleng Fm (D3h), and Lower Carboniferous Heishantou Fm (C1h). The Xiemisitai Fm, as the most widely distributed stratum in the area, is distributed in the northern part of the Yangzhuang granite and Yangzhuang fracture, and constitutes the main body of the Xuemistan mountain. The Hongguleleng Fm is distributed in the west Yangzhuang granite, while the Heishitou Fm is distributed in the south Yangzhuang fracture, spreading east–west. The intrusive rocks are late carboniferous granite porphyries interspersed with granodiorite. The spatial distribution of the granitic porphyry is strictly controlled by a deep Yangzhuang fracture (locally called Chagan Tolgoi—Bayanbulak). The overall distribution of the granitic porphyry is almost east–west, with an east–west length of ~10 km. In addition, the north–south width varies much, with a maximum width of 1.8 km and a minimum width of 0.1 km. Its area is about 6.9 km^2 [12]. The scale of diorite placed in the Yangzhuang granite is large and extending far, and the scale of alteration on both sides is relatively large. The syenite vein is smaller than diorite, the alteration on both sides is relatively weak, and fluoritization is developed on both sides. Some parts of aragonite are not exposed to the surface and can only be seen in wells.

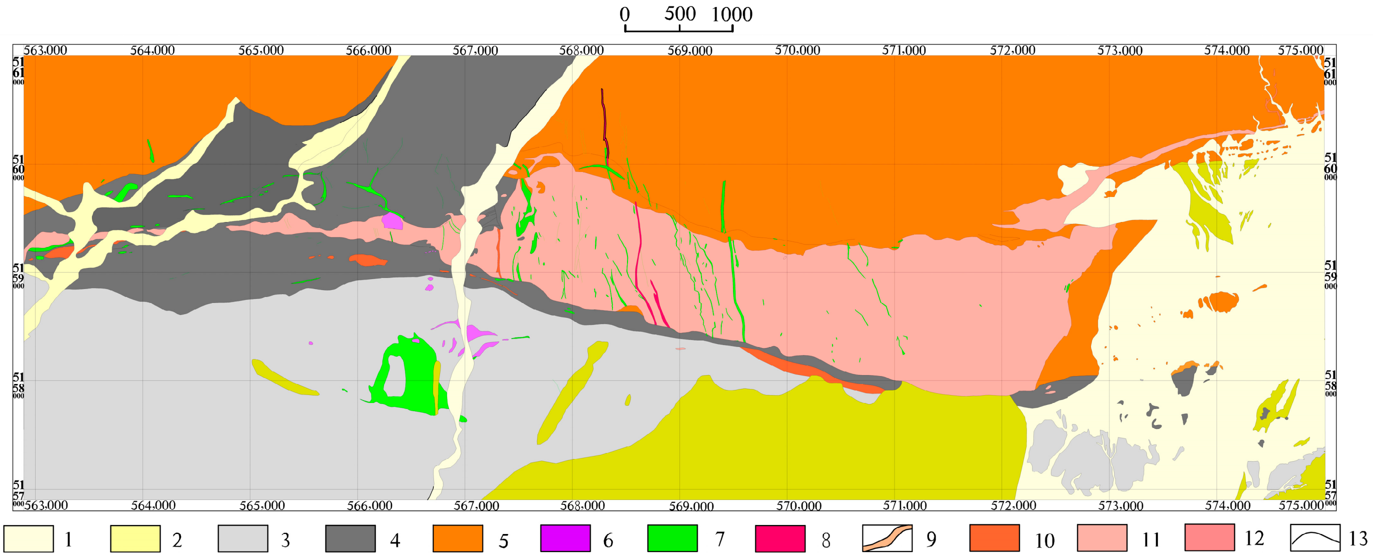

Figure 1. 3D geologic modeling range. 1—Quaternary; 2—Neogene; 3—Heishantou Fm; 4—Hongguleleng Fm; 5—Xiemisitai Fm; 6—Pyroxene diorite; 7—diabase; 8—Syenodiorite; 9—Syenite vein; 10—Tsingtauite; 11—Microcrystalline granite; 12—Silurian coarse-grained potassium granite; 13—Geologic boundary.

The Chagan Tolgoi–Bayanbulak fracture is called the Yangzhuang fracture in the Baiyanghe mining area. The fracture developed at the southern boundary of the Yangzhuang granite porphyry with a strike of about 100° and inclined at an angle of 65–75° to the north. The fracture structure controls the spatial distribution of the Yangzhuang granite porphyry and makes the rock distributed in the upper wall in the strip. It may be the passage of rock during the upward intrusion.

According to the statistics of uranium mineralization and uranium anomalies discovered in Yangzhuang, more than 95% of the uranium mineralization and anomalies are developed near the contact zone between the Yangzhuang granite and the lower strata. A few anomalies and extremely few industrial mineralization occur in fractures within the granite and in the strata below the contact zone, but they are usually within a distance of no more than 50 m from the contact zone. Some uranium anomalies are more than 100 m from the contact zone. Uranium mineralization far from the contact zone between the granite and the lower strata is usually weak and small.

3. 3D Metallogenic Prediction

The 3D prediction and evaluation of the Baiyanghe uranium deposit are based on the 3D geologic model in which favorable ore-controlling factors are extracted, and favorable metallogenic positions are calculated to define the target area and identify the location and evaluation of mineral resources. During prospecting, it is mandatory to establish the 3D geologic model before the establishment of the prediction and evaluation model. In addition, the 3D prediction model is formed based on the geologic background of the study area and by exploring favorable metallogenic information and extracting favorable prediction variables [13].

3.1. 3D Geologic Modeling

Based on the SKUA-GOCAD software modeling platform (University of Nancy, Nancy, France), the 3D geologic model for this project is adopted by integrating data from sectors such as geology, geophysical prospecting, geochemical prospecting, remote sensing, and drilling. With its characteristics of high data availability, comprehensive interpretation and mutual verification of the data, and high model precision, this method is the main development trend of 3D geologic modeling [14]. Through the combination of multisource data from the Baiyanghe deposit, the project deciphers the fracture lines of the Yangzhuang fracture in various sections and makes solid connections so that a 3D solid model of the Yangzhuang fracture is obtained. Similarly, the geologic boundary between strata and between the strata and the granite is identified, and the geologic interface is drawn by connecting the geologic boundary. Using the SKUA-GOCAD Model3d feature, the 3D geological model of the study area is finally established by obtaining the 3D solid model of stratum and granite by cutting the whole block with the well-prepared Yangzhuang fracture and according to the geologic interface from complex to simple (Figure 2).

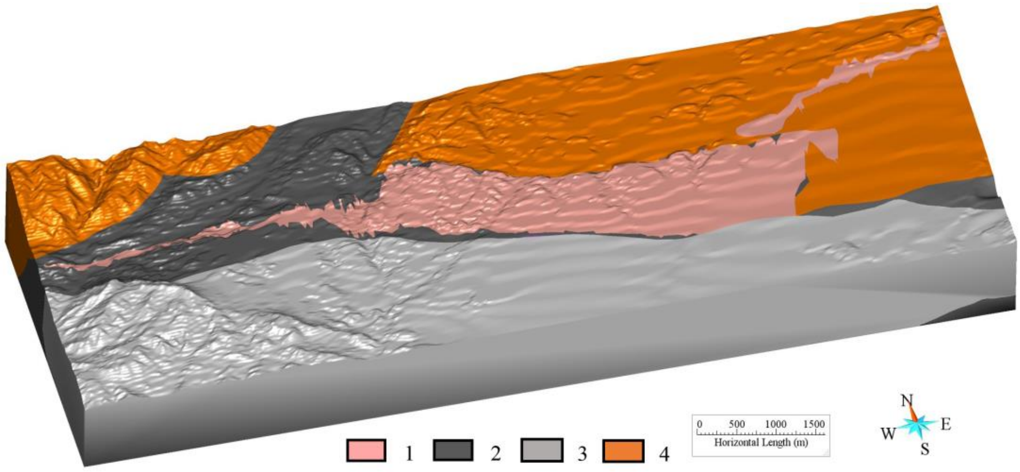

Figure 2. 3D geologic model of the Baiyanghe deposit and its perimeter. 1—Granite porphyry; 2—Hongguleleng Fm; 3—Heishantou Fm; 4—Xiemisitai Fm.

3.2. Extraction of Favorable Metallogenic Information

The range of the block model is determined according to the scope of the 3D geologic model in the study area. According to the modeling experience and the suggestion of the 3D software designer, the block size can be determined according to the extent of the exploration line network, the size of the ore body, the complexity of the ore body boundary, and the mining design requirements. In general, the block size can be 1/5–1/10 of the exploration line spacing. However, taking into account computer processing performance and data volume size, this study makes the classification of the unit block row × column × layer: 80 m × 50 m × 10 m, and the model includes 1,822,419 blocks. Taking the established 3D geologic model as a constraint condition, the author quantitatively extracted and analyzed the information of the ore-controlling geologic elements and also extracted favorable geochemical information, thus forming the quantitative prediction model of the study area [10].

3.2.1. Extraction of Information from Ore-Controlling Geologic Elements

Information about ore-controlling geologic elements includes information about the metallogenic structure, information about the rock bottom interface, and information about rock vein anomalies.

(1) Extraction of Metallogenic structure information

The fracture structure in the study area is the critical factor that controls the distribution of the uranium ore body. Uranium mineralization that has been found in the volcanic belt of Xuemistan has developed along a certain scale of fractures or fissures.

The uranium ore bodies near the contact zone between the Yangzhuang granite and the surrounding rock are relatively developed, and the reason is also that the fracture structure near the contact zone is relatively developed. The fracture structure acts as both the channels of the uranium metallogenic fluid and the site of the precipitation of uranium. When the uranium in the metallogenic fluid moves along the fracture or fissure, it allows for infiltration and metasomatic alteration to occur on the rocks on both sides, gradually increasing the uranium content in the solution. Then, uranium mineralization is formed by precipitation and enrichment in the appropriate structural environment. However, the metallogenic fluid cannot penetrate, or the penetration distance is very short in the section without fracture development, so a large uranium ore body cannot be formed.

The north contact zone of the Yangzhuang fracture was buffered 100 m to the north, which was extracted herein as metallogenic structural information (Figure 3). Quantitative analysis of fracture structure information usually includes isodensity, fracture frequency, fracture anomaly orientation, fracture orientation anomaly level, and main fracture. They, respectively reflect the spatial characteristics of linear structure and provide new and effective variables for prediction [15].

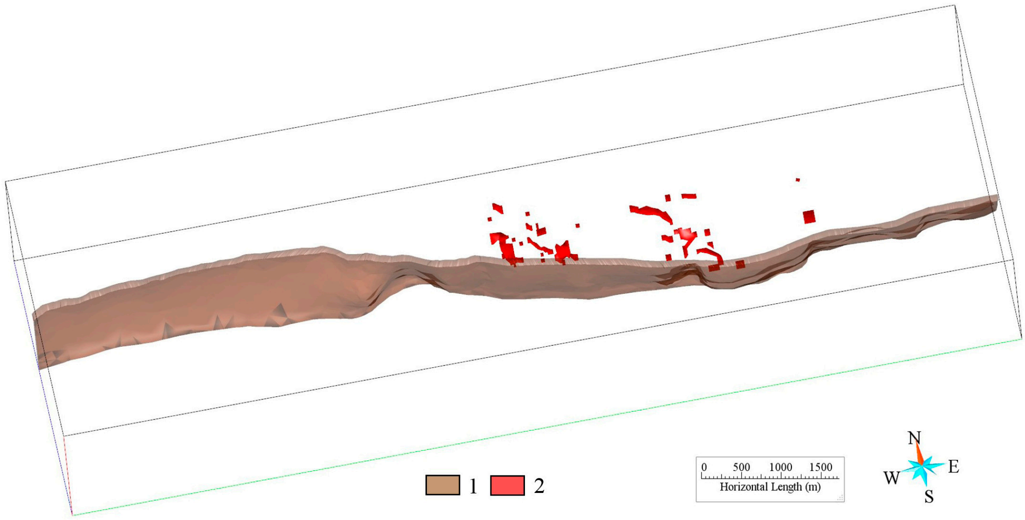

Figure 3. Buffer zone and ore distribution of the fracture structure in Baiyanghe mining area. 1—Buffer zone of the north contact zone of the Yangzhuang fracture; 2—Uranium ore body.

The higher the fracture isodensity, the stronger the structural development and the more concentrated the mineralization features. According to statistics, the interval (0.019–0.075) is the optimal distribution interval of iso-density (Figure 4), which is taken as favorable information for mineralization.

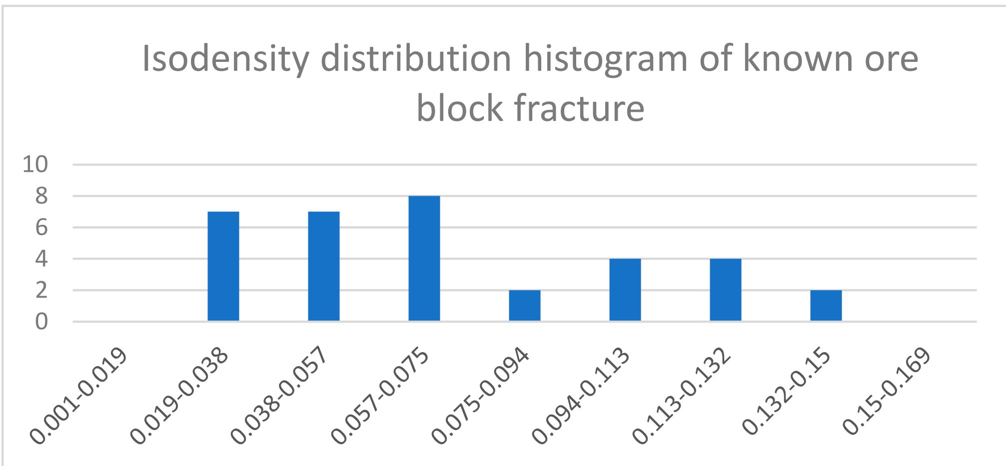

Figure 4. Isodensity allocation of known mineral-block fracture in Baiyanghe mining area.

Fracture frequency refers to the number of fracture structures produced in the section grid, which directly reflects the complexity of the regional structure, as well as the main characteristics of the regional structural framework [16]. According to statistics, the total number of ore bodies in the interval (0.52–0.98) accounted for about 70% of the total number of ore bodies, which would be taken as favorable metallogenic information.

The level of anomaly fracture orientation refers to the characteristic of the spatial orientation distribution of the structure of the statistics area, and the regional main structure generally controls the main structural orientation of the study area [17]. According to the superposition analysis of the quantitatively extracted orientation anomaly and the known ore body, the favorable interval is (0–0.02), (0.09–0.11), and (0.19–0.24).

The main fracture refers to the fault structure with large vertical depth and long horizontal extension, which is represented by the fracture isodensity/fracture frequency quantification. The higher the resulting value, the greater the total length of the fracture in the area; the smaller the number, the greater the opportunity for the development of a long fracture [18]. The study area has an east–west fracture and its structural orientation is shown in Figure 5. Through the quantitative extraction of the regional information on the main fracture and the analysis of the superposition of known ore bodies, the favorable quantitative metallogenic value range of the main fracture is (0.005–117.86).

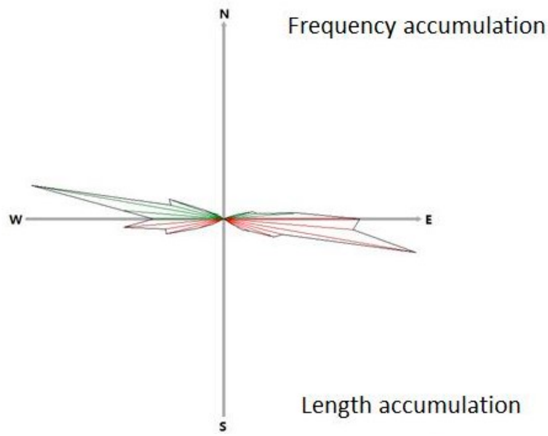

Figure 5. Structural orientation.

(2) Extraction of information of rock bottom interface

The industrial uranium ore bodies in the study area are mainly developed in the inner and outer contact zones of the Yangzhuang granite, focusing on the inner contact zone. The uranium ore body is usually developed in the range of several meters ~tens of meters from the contact zone. Large ore bodies are usually horizontal, developing in parallel along the contact boundary zone. Those developed in rocks or strata far from the contact zone are vertical. The smaller secondary ore bodies developed along structural fissures account for a limited number of resources in the deposit. It indicates the importance of the contact zone controlling the mineralization of uranium in this area.

According to existing exploration results, uranium mineralization occurs mainly within 50 m around the granite porphyry contact zone. Therefore, the upper and lower 50 m on the granite interface was taken herein as the granite bottom interface for information extraction. Eighty percent of the ore body is distributed in this area (Figure 6).

(3) Extraction of Rock Vein Anomaly Information

Yangzhuang granite have diabase and syenite vein. Their shapes are roughly the same, with an eastern inclination of 70–80°, a wide exposure range and a long extension distance on the surface. There is a close spatial relationship between veins, uranium bodies, and the alteration of red ferrite. Generally, the width of the alteration on both sides of the veins is 2–5 m. In this project, the veins buffered by 5 m to the left and right were taken as anomaly information of the vein for extraction (Figure 7). The width of the vein in the emplacement of granite porphyry varies. Therefore, a part of the vein of the Yangzhuang granite was selected for geologic modeling. After vertical block division of veins and known ore bodies, the statistical results show that a total of 58 ore bodies fall into the vein, accounting for 26.7% of the total ore bodies. Thus, it indicates that the vein anomaly information is directly related to the spatial distribution of ore bodies.

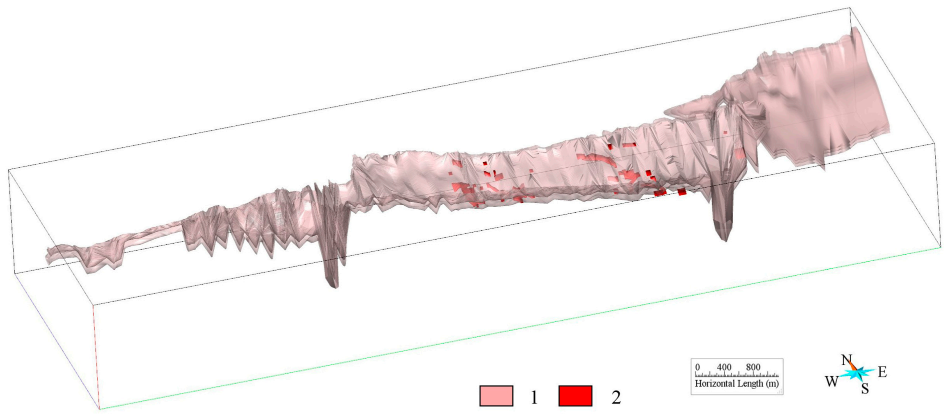

Figure 6. Relationship between the lower interface buffer zone of the granite and the uranium ore body. 1—The lower interface buffer zone; 2—Uranium ore body.

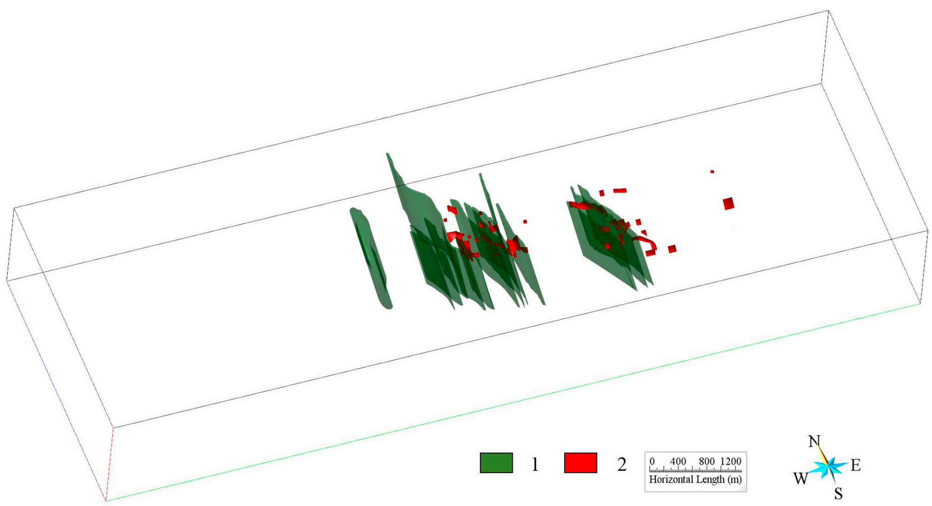

Figure 7. Distribution of the vein buffer zone and uranium ore bodies in the Baiyanghe mining area. 1—Veins buffer zone; 2—Uranium ore bodies.

3.2.2. Extraction of Geochemical Anomaly Information

Seven anomalies were determined herein, including the anomalies of the element U, Mo, Pb, Ba, Sr, soil Rn anomaly, and the ground gamma spectrum U anomaly. Statistics of the distribution of the geochemical anomaly area and known ore bodies were conducted by the vertical cube processing of geophysical anomaly areas (Figure 8). According to the results, the Ba anomaly area includes 0 ore block and 0% of the known ore block, the Mo anomaly area includes 21 ore blocks and 9% of the known ore block, the Pb anomaly area includes 11 ore blocks and 5% of the known ore block, the Rn anomaly area includes 21 ore blocks and 9% of the known ore block, the Sr anomaly area includes five ore blocks and 2.2% of the known ore block, the U component anomaly area includes 15 ore blocks and 6.6% of the known ore block, and the U energy spectrum anomaly area includes 218 ore blocks and 96.5% of the known ore block. Through superposition analysis, the anomaly of the U energy spectrum is highly correlated with the ore body. This means that the U anomaly of the gamma energy spectrum is closely related to the distribution of the uranium body, which can indicate the development of a deep ore body. Soil radon measurements and a component geochemical exploration were conducted mainly in the Yangzhuang granite and its perimeter, mainly in sections with a lower degree of uranium exploration. Therefore, the Ba, Mo, Sr, U component anomalies and soil Rn anomalies are poorly correlated with known ore bodies.

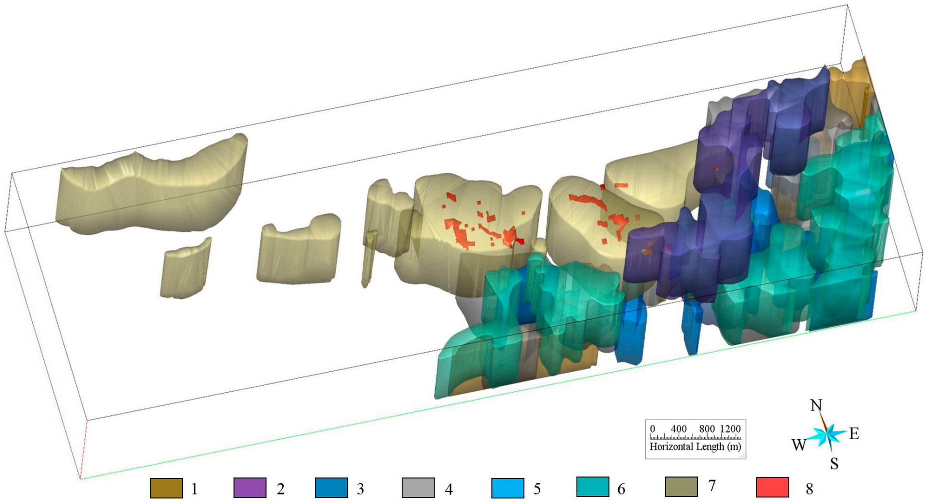

Figure 8. Relationship between geochemical anomalies and uranium ore bodies. 1—Ba anomaly; 2—Mo anomaly; 3—Pb anomaly; 4—Rn anomaly; 5—Sr anomaly; 6—U component; 7—U energy spectrum; 8—Uranium ore body.

3.3. Establishment of the Quantitative Prediction Model

According to the geological background of the study area and the analysis of the favorable metallogenic information, and according to the actual situation, the prediction model of the study area was established (Table 1). It was also agreed that the value of each marker in the unit is 1, and the value is 0 in the absence [19]. In other words, the block model was binarized to facilitate subsequent metallogenic prediction.

Table 1. Prediction model in the study area.

Category	Ore-Controlling Factor	Metallogenic Predictor	Characteristic Variable
Geology	Structure	Fracture buffer zone	100 m buffer area of fracture crushing zone
		Structural distribution characteristics	Fracture isodensity (0.019–0.075)
			Fracture frequency (0.52–0.98)
			Fracture anomaly orientation (0.59–0.63, 0.95–1)
			Anomaly level of fracture orientation (0–0.02, 0.09–0.11, 0.19–0.24)
			Main fracture (0.005–117.86)
	Granite's bottom interface	Favorable metallogenic area	50 m buffer area around the granite's bottom interface
	Rock veins	Favorable information about rock veins	5 m buffer zone around the rock vein
Geochemical exploration	Geochemical exploration	Geochemical anomaly information	Seven anomalies of Ba, Mo, Pb, RN, Sr, U component, and U energy spectrum

4. Prediction Results

The author conducted an analysis, summary, and correction of the geologic, metallogenic, and mathematical models in the study area, and used the 3D modeling software to conduct a digital simulation of the mining area and establish the cubic prediction model. According to the quantitative 3D cubic model, the author selected the appropriate mathematical method to perform the statistical processing of the data contained in the cubic unit. The author determined the favorable prospecting condition by calculation. Furthermore, the author made quantitative statistics on the proportion of known ore blocks in each favorable interval. According to the convergence of data statistics, the favorable degree limit is divided based on the percentage of known ore bodies in the favorable interval, and then the prospecting target area is determined [20]. Common mathematical methods for prediction include conditional probability analysis, characteristic analysis, the 3D weights of evidence, 3D information, factor analysis, the Monte Carlo method, etc. The 3D weights of the evidence method and the 3D prospecting informational method were used herein for location prediction.

4.1. Weights of Evidence Method

The weight of evidence method is a geostatistical method proposed by the mathematical geologist Agterberge (1998) to predict the mineral target area by superimposing and compounding the analysis of some favorable elements [21]. The weights-of-evidence method is composed of three parts: the calculation of the prior probability, the calculation of evidence weights, and the determination of the posterior probability [21]. According to the prediction model in the study area and taking the weights of the evidence method as a theoretic basis, the author calculated the weight of the metallogenic elements in the study area, which is given in (Table 2) [22], where W+ and W-, respectively, represent the weight in the area with or without the evidence factor, and the value C represents the relevance of the evidence factor and the relevance of the metallogenic [17]. According to the results of the calculation, the weight values of the U energy spectrum and granite bottom interface are high, indicating that the Baiyanghe uranium deposit is highly correlated with the U energy spectrum and granite bottom interface, and the control relationship needs to be further analyzed.

Table 2. Weight values of metallogenic elements in the study area.

Evidence Item	W+	S (W+)	W−	S (W−)	C
Mo anomaly	0.722296	0.217986	0.05099	0.069839	0.77329
Pb anomaly	0.631068	0.300863	0.02331	0.068196	0.654376
U energy spectrum	2.057473	0.067754	3.20329	0.352455	5.260766
Yangzhuang fracture	0.533274	0.288106	0.02254	0.068355	0.555818
Rock veins	2.666186	0.131367	0.27826	0.077144	2.944442
Granite's bottom interface	3.221804	0.074435	1.58029	0.14899	4.802094
Isodensity	0.614739	0.266816	0.02952	0.068676	0.644255
Anomaly orientation	2.480429	0.223493	0.08496	0.069669	2.565391
Frequency	1.155135	0.223372	0.06407	0.069669	1.219206
Anomaly level of orientation	1.902034	0.266896	0.05439	0.068676	1.956425
Main fracture	0.812505	0.171397	0.09358	0.072163	0.906088

The posterior probability value of each prediction unit is calculated according to the weight value of metallogenic elements, the interval is divided according to the value size, and different display colors are given (Figures 9 and 10).

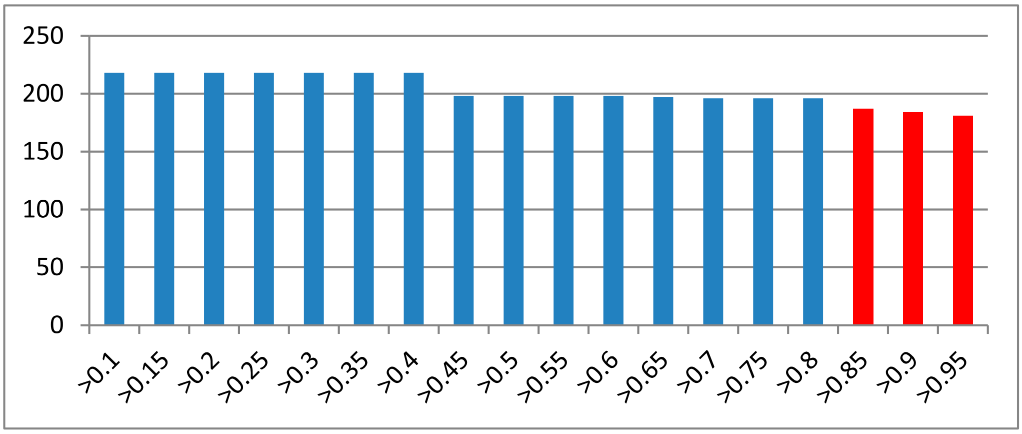

Figure 9. Posterior probability result.

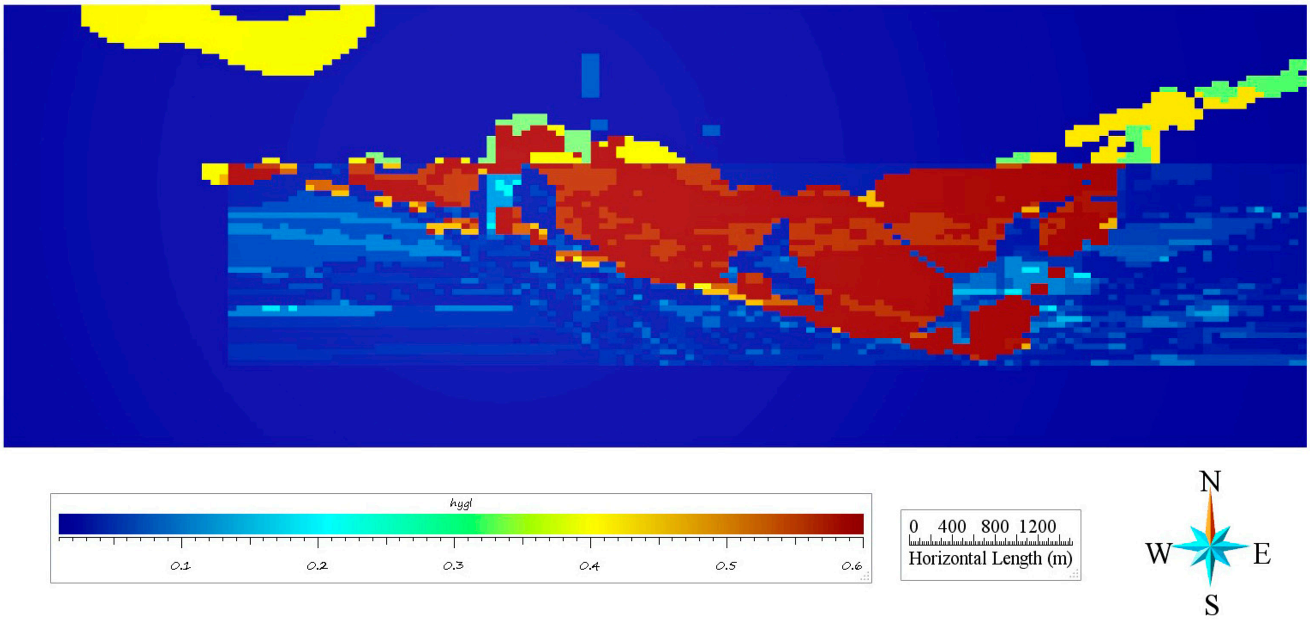

Figure 10. Posterior probability statistics, including known mining blocks.

According to the Figure 10, the posterior probability value changes sharply between 0.8 and 0.85. Therefore, the posterior probability value of 0.85 is selected as the minimum limitation condition for this prediction. According to statistics, a cubic block $\geq$ 0.85 contains 82.74% known ore bodies.

4.2. Informational Prospecting Method

The informational prospecting method is a nonparametric univariate statistical analysis method to study the indicating effect of geologic elements in prospecting prediction and evaluation by analyzing the distribution of various geologic elements in the study area. The sum of information from geological elements in the cube block in 3D prediction represents the significance of the prospecting of this block [11]. The information value of the metallogenic elements is calculated by quantitative analysis and statistics of the metallogenic elements in the study area (Table 3).

Table 3. Scale of information about metallogenic elements in the study area.

Information Layer	Number of Marker Unit	Number of Information Layer Unit	Information Volume Value
Mo anomaly	21	80,716	0.3202219
Pb anomaly	11	46,870	0.27545997
U energy spectrum	213	218,865	0.89316552
Yangzhuang fracture	12	55,794	0.23755598
Rock veins	56	31,996	1.14805457
Granite' bottom interface	175	57,373	1.38929272
Isodensity	14	59,756	0.27470875
Anomaly orientation	20	13,296	1.08227122
Frequency	19	49,727	0.48712358
Anomaly level of orientation	14	16,695	0.82850385
Main fracture	34	118,596	0.36237111

According to the table above, during statistics and analysis, it can be seen that the contribution of each metallogenic element to prospecting is relatively large, and that the contribution of two metallogenic elements of rock veins and the bottom interface of the granite to prospecting is relatively large. Based on these findings, the informational area is divided according to the size of the information, in accordance with the geological background and the metallogenic rule of the research area, and then the number of ore units contained in the informational interval is comprehensively counted [23] (Figure 11).

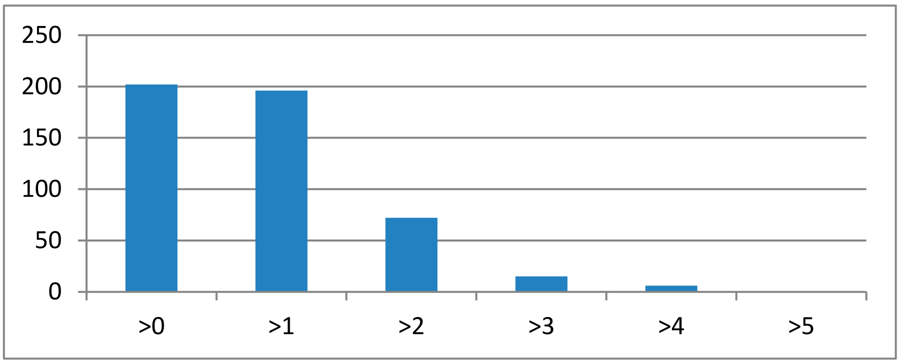

Figure 11. Statistics of the overlap of information with known ore body in the study area.

4.3. Analysis of the Prediction Results

Under the guidance of posterior probability interval and based on the finding of the informational value, the author calculates the ore block ratio (known ore block quantity in the information interval/total known ore blocks), the block ratio (total number of blocks in the information interval/total number of blocks in the study area), and the proportions of the ore block/block (Figure 12). According to the further statistics, as the information value increases, the ore ratio (ore block/block) has been converging, which further proves that the prospecting area prediction conforms to the statistics rule. Additionally, the ore block/block ratio is used to express the ore concentration. According to the posterior probability statistics rule [22], the information value is divided into two intervals: the information value is greater than 3, and the information value is less than or equal to 3 and greater than 1.

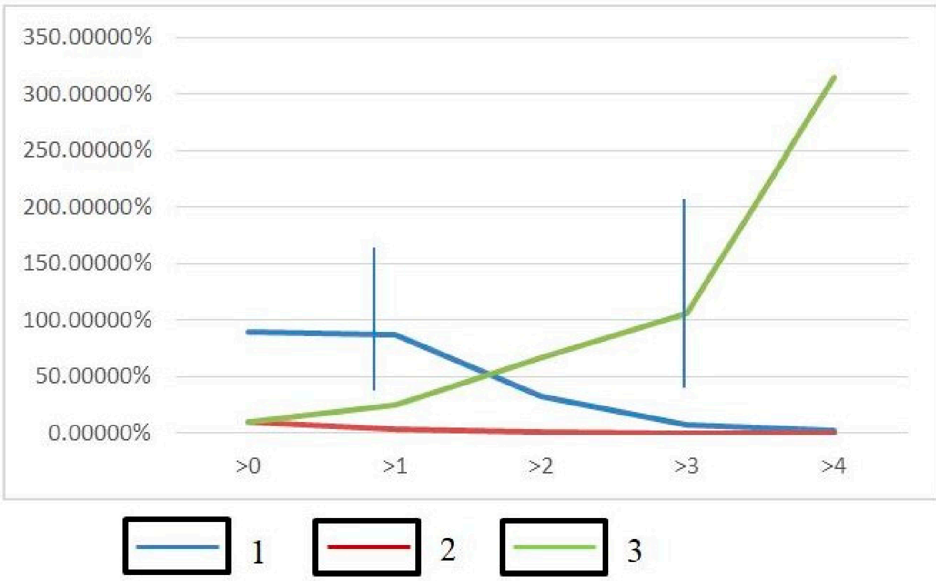

Figure 12. Regional informational statistics analysis. 1—Proportion of ore blocks; 2—Block proportion; 3—Ore-bearing ratio.

According to statistics, there are 1141 favorable metallogenic blocks with posterior probability ≥ 0.85 and informational magnitude > 3, accounting for 0.06 of 1,822,419 known cubic blocks in the region.

4.4. Delineation of Prospective Plans

According to the distribution of favorable metallogenic blocks, nine prospective areas A, B, C, D, E, F, G, H, and I were delineated within the 3D space of the study area (Figures 13 and 14). By superimposing the known ore body with the predicted favorable metallogenic block, we may see that the ore body has a good coincidence with the high-value region through a comprehensive prediction.

Prediction area A: East contact belt of the Yangzhuang granite. In this prediction area: X direction: 572,146 m–573,060 m; Y direction: 5,158,185 m–5,159,280 m; and Z direction: (290 m)–(1200 m).

Prediction area B: The magmatic emplacement channel in the southeast Yangzhuang granite. In this prediction area: X direction: 571,697 m–572,612 m; Y direction: 5,157,712 m–5,158,350 m; and Z direction: (40 m)–(1200 m).

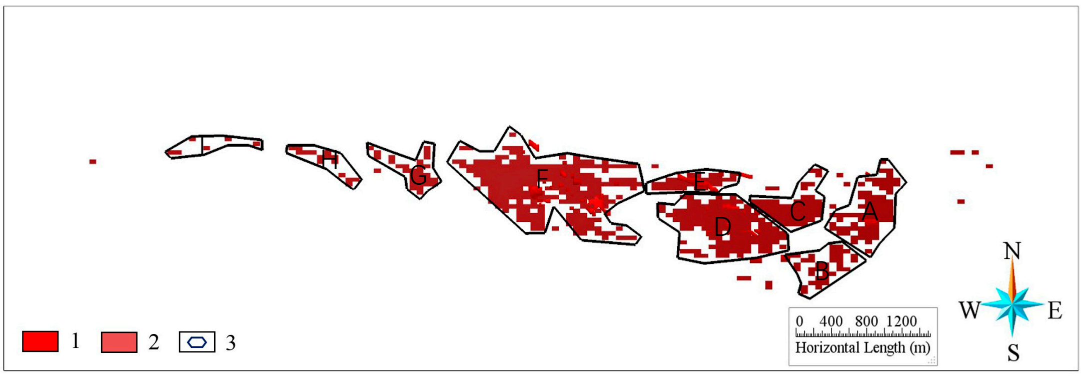

Figure 13. Distribution of the prospective metallogenic area (plane view). 1—Ore mass; 2—Favorable metallogenic block; 3—Metallogenic uranium prediction area.

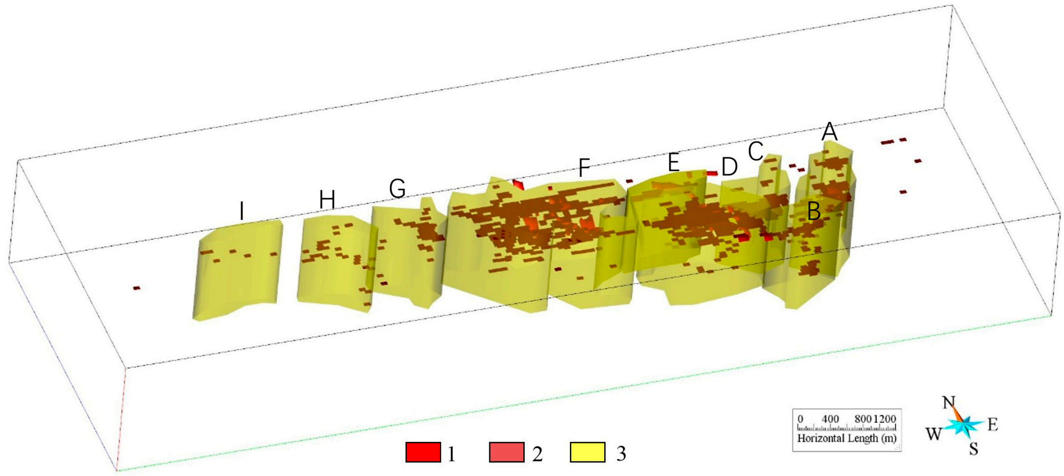

Figure 14. Distribution of the prospective metallogenic area (vertical view). 1—Ore mass; 2—Favorable metallogenic block; 3—Metallogenic uranium prediction area.

Prediction area C: No.7 site–central site section. In this prediction area: X direction: 571,297 m–572,177 m; Y direction: 5,158,464 m–5,159,224 m; and Z direction: (790 m)–(1200 m).

Prediction area D: Southeast No.2 site–No.5 site section. In this prediction area: X direction: 570,257 m–571,737 m; Y direction: 5,158,108 m–5,158,891 m; and Z direction: (90 m)–(1194 m).

Prediction area E: No.2 site. In this prediction area: X direction: 570,131 m–571,193 m; Y direction: 5,158,889 m–5,159,170 m; and Z direction: (94 m)–(1144 m).

Prediction area F: No.3–No.8 site section. In this prediction area: X direction: 567,887 m–570,076 m; Y direction: 5,158,316 m–5,159,652 m; and Z direction: (240 m)–(1190 m).

Prediction area G: No.9 site section. In this prediction area: X direction: 566,986 m–567,823 m; Y direction: 5,158,827 m–5,159,478 m; and Z direction: (244 m)–(1196 m).

Prediction area H: East Asuda granite. In this prediction area: X direction: 566,075 m–5,669,245 m; Y direction: 5,158,938 m–5,159,440 m; and Z direction: (40 m)–(1200 m).

Prediction area I: West Asuda granite. In this prediction area: X direction: 564,708 m–565,805 m; Y direction: 5,159,294 m–5,159,538 m; and Z direction: (740 m)–(1040 m).

4.5. Estimation of Prediction Resources

The resources are estimated to conduct a quantitative assessment of mineral resources based on the position, prediction, and evaluation of the mineral resources in the study area and the delineation of the prospective area [15].

Calculation formula for uranium resources:

$$Qm = \Sigma(Vi \cdot Ci \cdot \rho \cdot t \cdot k)$$

where Qm represents the metal content, Vi is the volume of the ore, Ci is the average grade of the ore, ρ is the specific gravity of the ore, T is the coefficient of bearing of the ore, and k is the correction coefficient. According to geostatistical analysis and findings from previous exploration reports, the average grade of the ore is 0.185% and the specific gravity of the ore is 2.62 t/m^3. To obtain a more accurate resource value in the prediction interval, the test has been carried out in the known ore body area, and an interpolation calculation is carried out in the known ore body area using the Krige method. The author then estimates the known ore body size of the resources and performs a comparative analysis with the metal scale of the known ore body area. The ore coefficient is 0.0008 according to the error. The correction coefficient by posterior probability is 0.85. On this basis, the resource delineated in the prediction area can be calculated.

At present, the identified uranium resources of the Baiyanghe deposit correspond to a medium to large scale, indicating that the Yangzhuang granite and its perimeter have good metallogenic potential. Ten metallogenic prospective areas of uranium have been predicted, and three uranium prospecting target areas have been delineated. We further predict that the area has rich potential uranium resources. It should be noted that this study has carried out drilling in the prospective area A and B predicted. Five uranium industrial holes, two uranium mineralized holes, four beryllium industrial holes, two molybdenum industrial holes, and one molybdenum mineralized hole are newly found. Breakthroughs have been made in uranium multimetal prospecting, and newly added uranium resources.

5. Conclusions

(1) A 3D geological model is established by systematically collecting, arranging, and analyzing the multisource data of geophysical and geochemical exploration, remote sensing, and drilling in the Baiyanghe study area, thus achieving breakthroughs and the application of 3D modeling technology for complex geologic objects. The complex deep geological environment and its controlling effect on uranium mineralization have been comprehensively and intuitively analyzed from the 3D perspective. Therefore, we have obtained a more profound understanding of the uranium mineralization and control rules.

(2) Based on the Baiyanghe uranium deposit model and through the analysis of the metallogenic rule, the prediction model is then established by extraction of elements such as structure, granite bottom interface, rock vein and geochemical anomaly, and the qualitative analysis of 3D correlation of ore-bearing and ore-controlling property. We then performed a quantitative analysis and extraction of elements, and provided element data for 3D quantitative prediction.

(3) To improve the accuracy of 3D quantitative prediction, the 3D weights of the evidence method and the 3D information method are used for the quantitative analysis of the ore deposits. Through the comprehensive application of the prediction and analysis results, the author obtained the favorable high-value area and delineated nine potential areas. It further showcases that the Baiyanghe uranium deposit and its perimeter have a greater prospecting potential.

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Conflicts of Interest: The authors declare no conflict of interest.

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