APPLICATION OF GEOSTATISTICS IN THE ESTIMATION OF SUJISHAN GRAPHITE DEPOSITS, MONGOLIA

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ABSTRACT

In this paper, the author used mine 3D software to establish the 3D geological model of Sujishan Graphite deposit, and applied geostatistics to estimate the resource, offered references for next exploration and mining. Surpac was used to set up geological database of Sujishan Graphite deposit, topographical DTM, ore body model and grade model, 3D of drilling database, also analysis the spatial grade distribution in reality. Based on geostatistics, drilling samples are composited and statistically analysed and eliminate the impact of outliers. Experimental variograms were constructed for the striking, dipping and vertical directions. Grade and resource are estimated by ordinary kriging. Comparing to the traditional estimation methods, this 3D software gives reliable estimation, which provides references for dynamic management of mine's resource.

KEYWORDS

Surpac software, 3D model, Geostatistics, Ordinary kriging, Resource estimation

INTRODUCTION

Geostatistics is based on regionalized variables and uses variability as a tool for research. It is a science that studies natural phenomena that are both random and structural, or spatially related and dependent. Any research related to the structural and random nature of spatial data, or spatial correlation and dependence, and any optimal unbiased interpolation estimation of these data, or simulation of the discreteness and volatility of these data can be researched based on geostatistics. The famous French statistician Georges Matheron first proposed the concept of geostatistics in the article Traité de géostatistique appliquée [1]. Professor Matheron proposed the concept of regionalized variable based on his own research results, and finally created geostatistics subject. According to geostatistical theory, geological features can be represented by the spatial distribution characteristics of regionalized variables. In the process of studying the spatial distribution characteristics of regionalized variables, Variogram is often used as the main research tool for analysis. The similarity between geostatistics and classical statistics is that they all need enough samples first, and then determined by analysing the relationship between the frequency distribution of the sample attribute values or the mean, maximum and minimum, variance, standard deviation and their corresponding relationship, spatial distribution characteristics and correlation. The differences between geostatistics and classical statistics include: classical statistical research subjects are mainly pure random variables, while geostatistical research subjects are mainly regionalized variables; classical statistical requirements can be used for repeated sampling and observation experiments, etc., and the variables studied by geostatistics are generally not capable of repeated sampling and observational experiments; the data of classical statistical studies is independent of each other and the data of geostatistical studies is spatially correlated; classical statistics are studied by frequency distribution maps. And geostatistics is based on spatial distribution characteristics [2, 3].

The three-dimensional geological modelling can reflect the results and characteristics of the ore body, which enables the geologists to have a more intuitive and clear understanding of the ore body. Since the 1990s, a large number of 3D geological software based on geostatistical theory has been developed globally. The theory of geostatistics has been continuously supplemented and improved. At the same time, geostatistical analysis and commercial software have sprung up. IDRISI, GEO-EAS, GS+, Surfer, GeoDA, Surpac, Datamine, Vulcan, CGES, 3Dmine, DIMINE and other pieces of software are representative development software. [4, 5] With the continuous development of geostatistical theory, new geostatistical algorithms are gradually integrated into geostatistical software. Stanford University's GSLIB and SGEMS are the two most representative of the software, a large number of random simulation algorithms and other application modules are integrated into two pieces of software.

In this study, the Surpac mining software was used to construct a three-dimensional model of the Sujishan graphite deposit in Mongolia, and the grade distribution of the Sujishan graphite deposit was statistically analysed. The Ordinary Kriging method based on geostatistical theory was adopted, and the grade original data was used. The ore body parameters were estimated and finally the distribution of mine resource quantity is obtained, which provides technical support for the optimization of mine resource quantity control and the establishment of “digital mine” [6-8].

Geological characteristics of the mining area

1) Formation: The project area is located in the Xingmeng orogenic belt between the North China and Siberian land masses and forms the eastern part of the Ural-Mongolian metallogenic belt. The sedimentary strata in the mining area are mainly the Upper Proterozoic - Cretaceous strata. The Permian - Cretaceous strata are mainly distributed in the southeast of the mining area. Both strata are unconformity contact relationships which are controlled by the structure. Graphite - bearing shale is controlled by structural alteration zones.

There is a small number of metamorphic rocks of the Upper Proterozoic and sedimentary rocks of the Lower Cretaceous in the mining area. The earliest metamorphic rocks are part of the green schist in the combination of Delong (NP2-3 do), and the overlying rock Sujishan (NP3-su) is a combination of natural graphite schist, Chaganwula (NP3 cu) combined limestone, etc. The youngest rock is the relatively loose sediment of the Lower Cretaceous Ulande (K1-ud) combination.

2) Structure: The fractured structures in the mining area are developed in the NE - NEE and near SN faults, both of which are post-mineral faults. In the mining area, there is a monoclinic structure that is gently inclined to the southeast. The meridional structure is formed only at the northeast end of the mining area, so that the ore belt is divided into two parts with a fault contact in the middle. In the direction of the fold hub, the lithology of the core at 32° northeast is limestone. The obliquely turned end and the west wing are cut by F3 fracture, and the main ore belt on the west side is divided into two parts.

3) The magmatic rocks: Magmatic rock are widely distributed, mainly intrusive rocks, which belong to the Caledonian and Early Hercynian, respectively. It is mainly composed of gabbro, diorite, quartz diorite, biotite granite and a small amount of alkaline white granite in the Devonian invasion. The eruptive rocks are mainly Yingan, Andesite, and Liu Rocks and tuffs. The formation of graphite

DOI 10.14311/CEJ.2018.04.0039

ore in the area is closely related to frequent magmatism and regional metamorphism. The intrusive activity after mineralization is only limited quartz vein, which has little effect on the deposit.

4) Characteristics of ore bodies: The graphite ore body in the mining area is located in the upper part of the Upper Proterozoic Sujishan combination metamorphic rock series. It is a set of graphite schist layer containing sericite schist. Through the surface geological and drilling verification work, the different sized graphite ore bodies are exposed in the mining area whose number is about 20. The elevation of the ore body is in the range of 1271~1286m above sea level. The ore body is layered and undulated along the stratum. The clusters are arranged in parallel, the ore bodies are about 30~50m apart, and the ore body overall striking is 40~42°, dipping to the south, gently inclined, and the dip degree is 5~47°.

5) Ore composition: The ore structure is a fine-grained Granitic metamorphic texture. The ore structure is a schistose structure, banded structure, dense massive structure. The ore mineral in the ore is graphite, and the gangue minerals main include quartz (5~49%), sericite, biotite, lithium mica (10~15%), goethite, limonite, chlorite, and pyroxene, copper ore, etc.

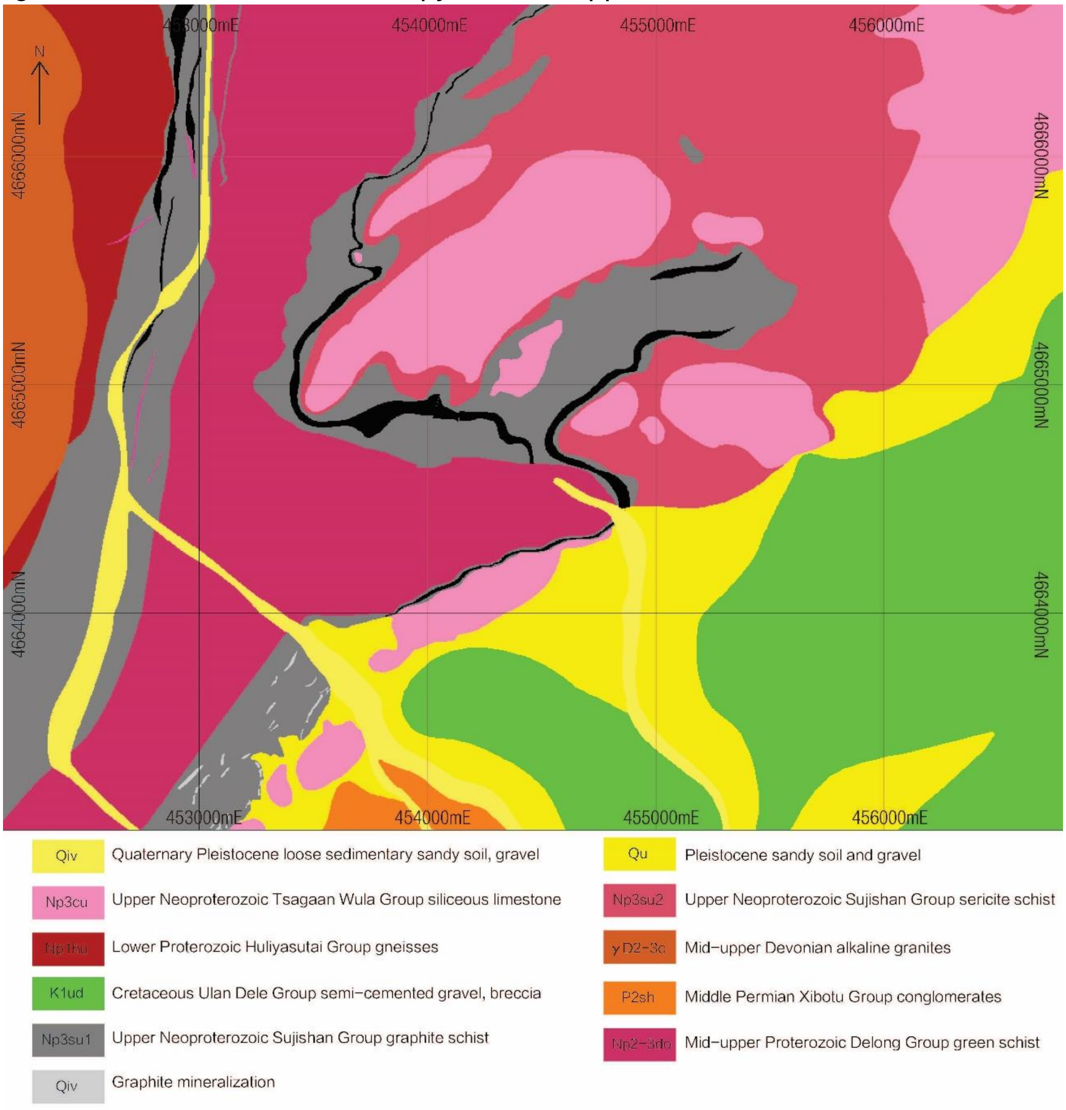

Fig.1 - Geological map of the Sujishan graphite deposit in Mongolia

DOI 10.14311/CEJ.2018.04.0039

Model construction and resource esttionima

Database construction

The database establishment procedure mainly includes collecting all exploration data in the mining area. The geological data includes trenching, drilling and pit exploration results which can be used for recording the distribution of lithology and faults through geological logging, and then importing the data into Surpac to establish a 3D geological database with proper format. The use of geological databases to store geologically relevant information can establish a three-dimensional geological model of the mining area more accurately and completely and construct the foundation for subsequent resource estimation. In this paper, the relevant geological information of 85 boreholes and trenches in the mining area were collected, and four basic tables such as collar, survey, assay and lithology tables were established. Among them, the collar table mainly includes the collar coordinates of the borehole, drilling depth, drilling type, drilling time and hole path; the survey table mainly includes the azimuth and dip of the drilling and the depth of the inclination; the assay table mainly includes the sample assay results (mainly including grade information of total carbon, graphite carbon and other elements); the lithology table mainly includes information of rock types, strata, minerals, alterations and so on. Finally, the established geological database is verified in 3D software, and the digital terrain model (DTM) and the 3 digital model (3DM) are created by Surpac software as we can see in the Figure 2 below.

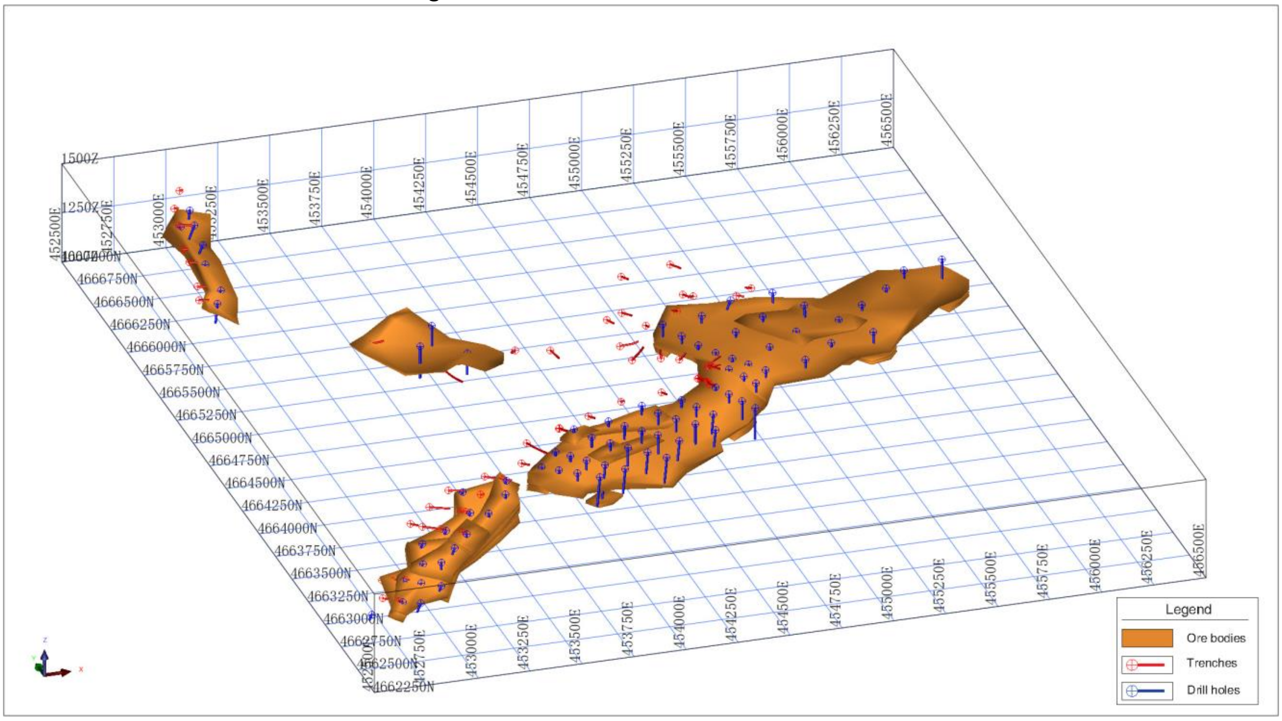

Fig. 2 - 3D view of the ore body and borehole

Composite sample and variogram analysis

Geostatistical analysis of the database data, and the estimation of the block model with using the sample grade or body weight value, both require that each sample has the same weight, the sample length of each sample is consistent. Thus, we can ensure that the analytical calculation results are in reasonable estimation process. Therefore, it is essential to perform a composition of samples before performing basic statistical analysis and variogram analysis of the samples. There are various methods for compositing samples, such as compositing along drilling direction, compositing by bench, compositing by geology domain, and internal compositing in the ore bodies. At this time, the combination of compositing along drilling direction and compositing by geology domain method was applied. In the process of sample compositing, various factors that may affect the determination of the length of the compositing sample were considerred, such as the average length of the original samples, the exploration spacing, the minimum mining unit, the block model block size, and so on.

A graphite mineralization wireframe ("domain") was used to encode the assay database to allow identification of resource intersections. The length of the sample is then checked to determine the optimal composite length. The most common sample length inside the mineralized wireframe is 2 meters, so this length is chosen as the sample composite length and Surpac is used to extract the composite sample. After the sample compositing, the graphite carbon data was statistically analyzed by statistical software of Supervisors. The analysis results showed that the composite samples still follow the lognormal distribution (Figure 3a, Figure 3b), indicating that the grade of graphite carbon is still a continuous random variable after the sample compositing. This provides a prerequisite for experimental semivariogram analysis. Although simple statistical analysis can reflect the global characteristics of the geological body, it still cannot reflect the changes of the sample in the local range and specific direction (striking, dipping, and vertical). Compositing the samples, and then analyzing the semivariogram of the composited results is a good solution to the problem of analyzing local geological features.

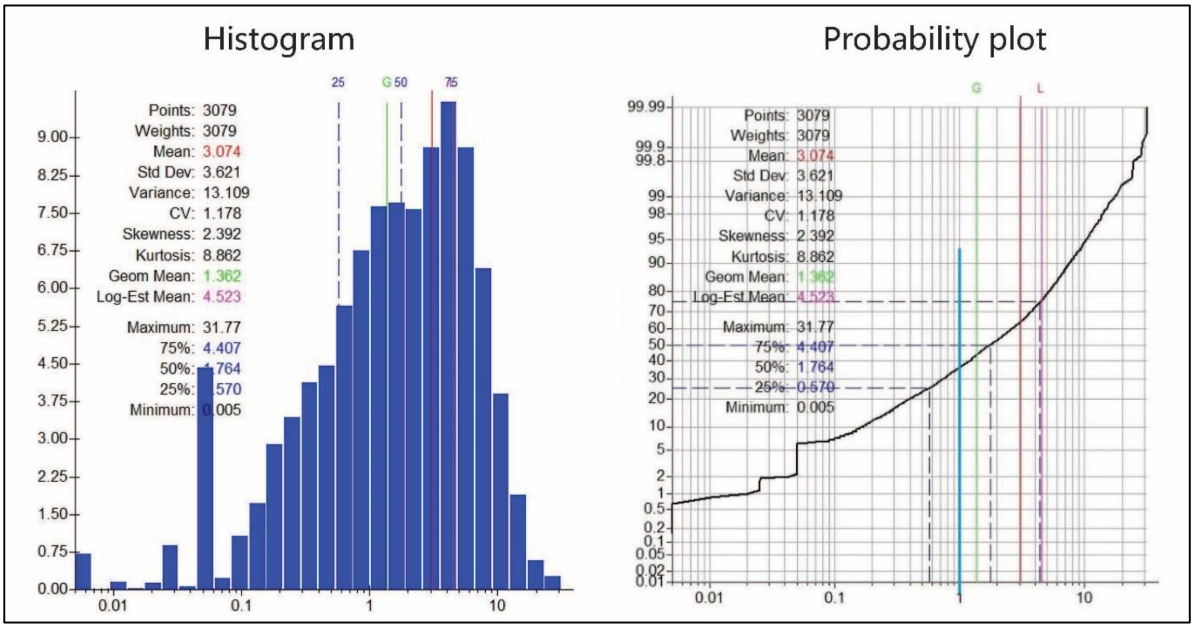

Fig. 3 - sample histogram and probability distribution

Variogram analysis

In order to describe the variability of the ore grade distribution in the deposit, we often use the mean, maximum value, variance, standard deviation and other parameters of the sample as analytical tools for common statistics, and these statistics can only summarize the characteristics of the samples. The global characteristics of the values do not simply reflect changes in the sample and in a particular direction. The introduction of experimental variograms into geostatistics can accurately reflect the correlation and randomness of regionalized variables, especially the stochasticity of grades to reflect the structurality of regionalized variables. As the spatial distribution of the ore body is often not exactly the same in different directions, the so-called spatial anisotropy, the regionalization variable can be used to characterize the mine that changes continuously according to different directions. In the analysis and calculation of the experimental semi-variogram, the main mineralization extension direction, the secondary mineralization extension direction and the third mineralization extension direction will be analysed. Hypothetical regionalization variable $Z(x)$ satisfy the second-order stationary hypothesis and the eigen hypothesis, whose mathematical expectation is m, covariance function and variogram $c(h)$ exists, according to the basic concept of geostatistics, the variogram formula is as follows:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \tag{1}$$

In formula (1), $N(h)$ Is the step size, h is the number of pairs of data; $Z(x_i)$ with $Z(x_i + h)$ is a two-point sample value that is separated by h. Because the variogram is a statistical method, the more samples are taken at a certain step size, the more reliable the variogram estimate is.

When performing a simple Kriging estimate, we assume that the average of the entire region is known, but in fact the overall mean is difficult to be found directly, unless the mean of the known sample points is used to represent the overall sentence. The ordinary Kriging estimation method does not depend on the mathematical expectation that the random variable $Z(x)$ is known for all x . The ordinary Kriging interpolation formula is:

$$Z^*(x) = \sum_{i=1}^{n} \lambda_i Z(x_i) \tag{2}$$

In formula (2) $Z(x_i)$ is the sample value, $Z^*(x)$ is the estimated value, λ_i is the weight coefficient, indicating the extent of contribution of sample value $Z(x_i)$ to estimated value $Z^*(x)$ at a spatial sample point x_i .

In order to calculate the weight coefficient λ_i under the condition that the two conditions of unbiased estimation and optimal estimation are satisfied, the calculation is based on the Lagrangian principle, and the Kriging equation (3) is obtained:

$$\begin{cases} \sum_{j=1}^{n} \lambda_j c(x_i, x_j) - \mu = c(x_i, x) \\ \sum_{i=1}^{n} \lambda_i = 1 \end{cases} \tag{3}$$

In formula (3) $c(x_i, x_j)$, $c(x_i, x)$ are the covariances, μ is the Lagrange multiplier.

Find the weight coefficient by solving the above linear equations λ_i and Lagrangian coefficient u , substituting to the following formula (4) we can obtain the Kriging estimated variance

$$\sigma_E^2 = c(x, x) - \sum_{i=1}^{n} \lambda_i c(x_i, x) + \mu \tag{4}$$

In formula (4), $c(x_i, x_j)$, $c(x_i, x)$ are the covariances, μ is the Lagrange multiplier.

DOI 10.14311/CEJ.2018.04.0039

For the project we used a spherical model as a variogram model to analyse all data. The standard form of the spherical model is as below:

$$\gamma(h)=\begin{cases}\frac{3}{2}\frac{h}{a}-\frac{1}{2}\left(\frac{h}{a}\right)^3 & h\le a\\ 1 & h>a\end{cases} \tag{5}$$

In equation (5), a is the range and h is the distance between the two samples.

In this analysis, the ore-dominated ore body 10 was selected as the main research object for variogram analysis and parameter extraction. According to the principle of geostatistics, the sample logarithm can be selected to find the maximum number of down hole directions within a certain search radius, and then the nugget value data is obtained (Figure 4a). The direction of the down hole is substantially perpendicular to the plane determined by the first and second mineralization directions (depending on the rationality of the initial exploration engineering design). Geostatistics uses the variogram as the most important research tool. Whether it is used for structural analysis of regionalized variables or for interpolation of other samples, the variogram obtained in the previous direction must be in several main directions. The fitting was performed (Figure 4b, Figure 4c, Figure 4d). According to the theoretical variogram model, the variogram model which is actually used for valuation calculation in all directions of the ore body is determined, and its parameters (variable range, base value, nugget value, etc.) are obtained [9-10].

In this paper, according to the striking, dipping and vertical direction, the variogram of the graphite carbon grade is fitted and calculated. The calculation results are shown in Table 1.

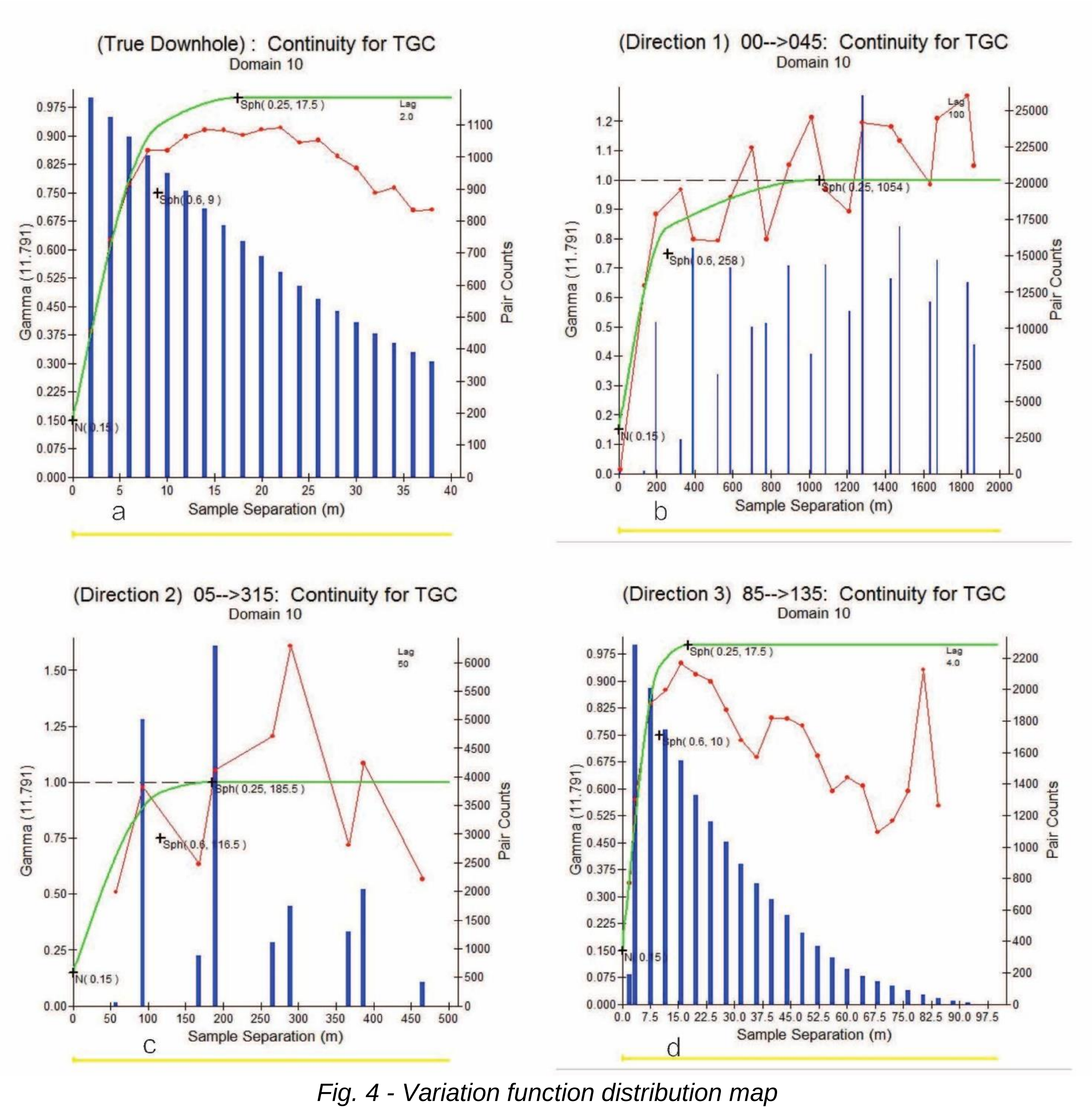

Fig. 4 - Variation function distribution map

Tab.1 - variogram analysis results table

ingredient	direction	Axis directio n	Block gold value	Structure 1				Structure 2			
				Abutme nt value	Ra ng e	Primary and secondary axis ratio	Main short axis ratio	Abutment value	Ra ng e	Primary and secondary axis ratio	Main short axis ratio
Total graphitic carbon	Spindle direction	00-- >045	0.15	0.6	10 0	2.2	25.8	0.25	10 0	5.7	60.2
	Secondary axis direction	05-- >315	0.15	0.6	50			0.25	50		
	Short axis direction	85-- >135	0.15	0.6	4			0.25	4		

Variogram validation

The rationality verification procedure is used to test the rationality and correctness of the grade estimation results based on the parameters obtained by the variogram curve fitting. Firstly, the estimation results of each ore body are compared with the historical inverse distance method and the average grade of the composited samples. The comparison results are shown in the following Table 2. According to the statistical results, the estimation results are stable, for all primary and secondary ore bodies, the actual estimation errors of the ore bodies are within 5%.

Tab.2 - Sujishan Resource Block Model Verification Table

Area	Wireframe	Block model				Composited sample		Data deviation		
	Wireframe volume	Resource model total volume	Resource model estimation volume	Graphite carbon_IDW %	Graphite Carbon_OK %	Number of composites	Graphite carbon %	Volume	Inverse ratio	Ordinary krig
1	5,283,216	5,270,703	5,202,734	4.18	4.26	152	4.28	-0.24	-2.33	-0.46
2	2,310,000	2,298,828	2,230,469	3.52	3.50	78	3.37	-0.48	4.35	3.68
3	2,905,220	2,889,844	2,889,844	4.68	4.60	66	4.56	-0.53	2.53	0.76
4	529,299	532,813	514,063	2.50	2.65	16	2.31	0.66	8.41	14.85
5	160,201	162,500	161,719	2.89	2.90	4	3.30	1.44	-12.41	-12.12
6	156,857	158,984	136,328	2.53	2.44	4	2.46	1.36	2.75	-0.76
7	306,096	304,297	304,297	2.86	2.81	7	2.83	-0.59	1.08	-0.71
8	132,021	130,469	130,469	2.71	2.57	4	2.48	-1.18	9.21	3.64
9	3,921,001	3,915,234	3,793,750	3.62	3.21	52	4.12	-0.15	-12.20	-22.09
10	64,484,474	64,084,766	64,048,828	5.20	5.22	1249	4.63	-0.62	12.35	12.71
11	738,644	730,469	730,469	4.55	5.10	11	4.38	-1.11	3.77	16.49
12	274,754	268,750	268,750	3.24	3.60	4	3.22	-2.19	0.61	11.71
13	378,390	372,266	372,266	2.13	2.15	6	2.26	-1.62	-5.54	-4.65
14	317,343	320,313	320,313	1.08	1.12	5	1.11	0.94	-2.37	0.94
15	677,822	679,297	679,297	1.46	1.36	8	1.50	0.22	-2.84	-9.08
16	2,894,215	2,889,453	2,889,453	2.85	2.88	50	2.89	-0.16	-1.28	-0.42
17	155,569	160,547	160,547	4.98	5.38	3	4.99	3.20	-0.29	7.90
18	294,667	291,797	291,797	4.03	4.89	10	3.76	-0.97	7.09	29.96
19	16,234	15,625	15,625	7.30	7.30	1	7.30	-3.75	0.00	0.00
20	149,091	150,391	150,391	3.09	2.96	5	2.70	0.87	14.50	9.56
21	23,439	23,828	23,828	10.38	10.38	1	10.38	1.66	0.00	0.00
22	260,535	250,391	250,391	2.39	2.36	9	2.33	-3.89	2.76	1.43
23	37,652	35,547	35,547	2.28	2.30	2	2.27	-5.59	0.52	1.21
24	35,276	32,031	32,031	4.46	4.46	2	4.46	-9.20	0.00	0.00
25	44,805	42,578	42,578	4.60	4.79	3	5.00	-4.97	-7.97	-4.25
26	9,190,205	9,192,188	9,190,234	5.73	5.53	180	5.45	0.02	5.14	1.38
28	364,902	360,938	360,938	5.26	5.12	13	5.69	-1.09	-7.51	-10.03
29	109,361	109,766	109,766	5.03	5.11	6	5.20	0.37	-3.20	-1.74
Total	**96,151,289**	**95,988,285**	**95,336,722**	**4.90**	**4.88**	**1,951**	**4.49**	-0.17	**9.08**	**8.75**

At the same time, after completing the macroscopic comparison of the estimation results of each ore body, the deviation between the graded values and the true values in each section of the ore body are plotted, and the difference and change are statistically analyzed as Figure 5 (X and Y directions). Through the analysis of the block model swats plots, we can see that the estimation result curve and the original data curve have a high degree of fitting in each ore body segment, which confirm the high correlation between the estimation results and the original composited results. Meanwhiles, some high-grade sections are processed by the Ordinary Kriging estimation method, the smoothing effect leads to a more reasonable grade distribution. Each segment-related block is combined with a reasonable number of original samples for estimation, and the reliable estimation results are obtained as well.

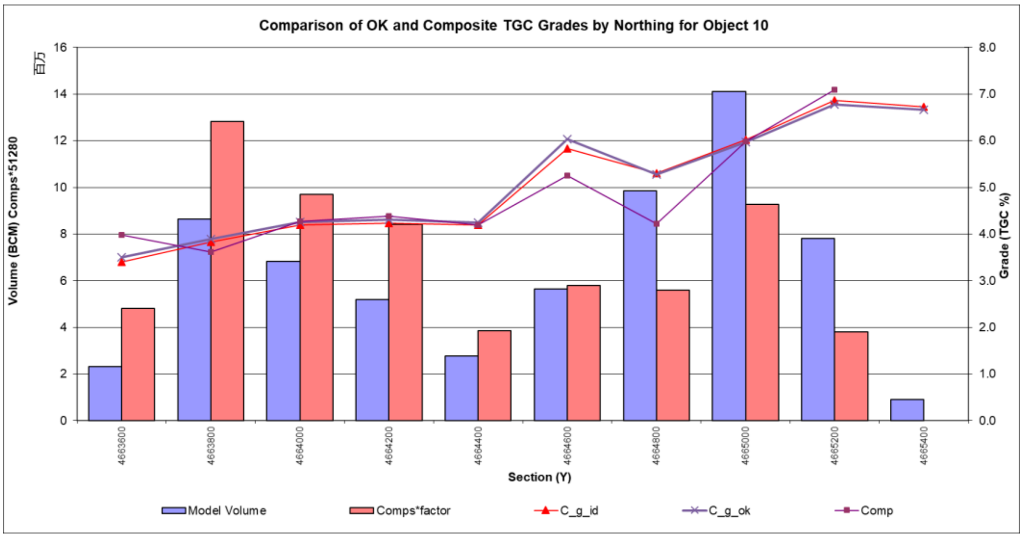

Fig.5 - Resource quantity estimation result segmentation chart verification result (X, Y direction)

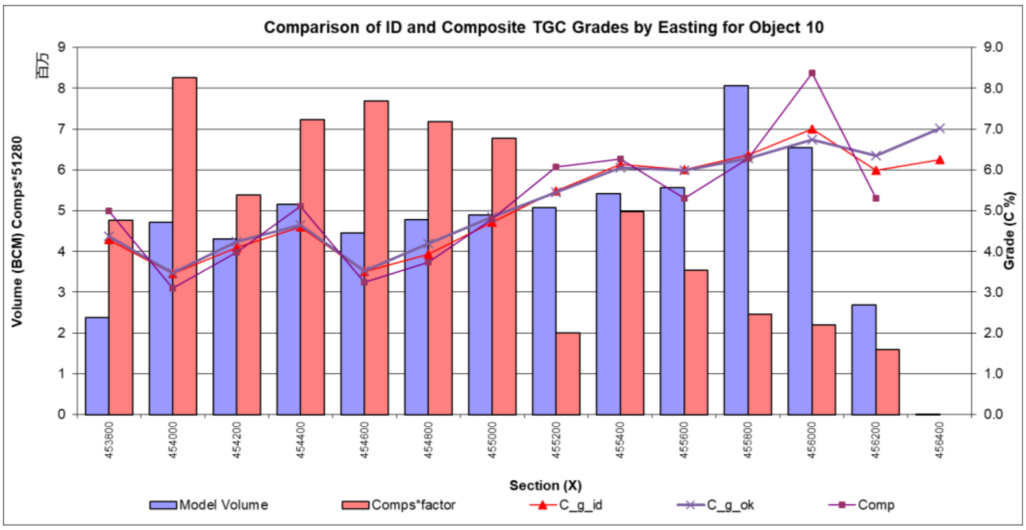

Fig.5 - Resource quantity estimation result segmentation chart verification result (X, Y direction)

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DOI 10.14311/CEJ.2018.04.0039

Resource estimation

In this study, a block model was created in the mining area, covering the mineralization range of the whole ore body, and constrained by the ore body solid model. The block size of the block model selected for this resource estimation is 50m×100m×5m. The sub block size is 12.5 m x 25 m x 1.25 m. The composited sample string files were obtained by sample compositing, and the string file data was extracted to perform the grade estimation of the remaining unknown blocks in the block model. The estimation method selected was the ordinary Kriging method, and the relevant parameters such as nugget and the sill and range obtained by fitting the variogram model were obtained and imported into the 3D geological software to estimate all relevant blocks in the block model (Figure 6). The calculation formula is as follows.

$$Q_m = C_i \times V_i \times \rho \qquad (6)$$

In formula (6), Q_m is the amount of metal, V_i is the bulk volume, C_i is the average grade of the block, ρ is the ore weight.

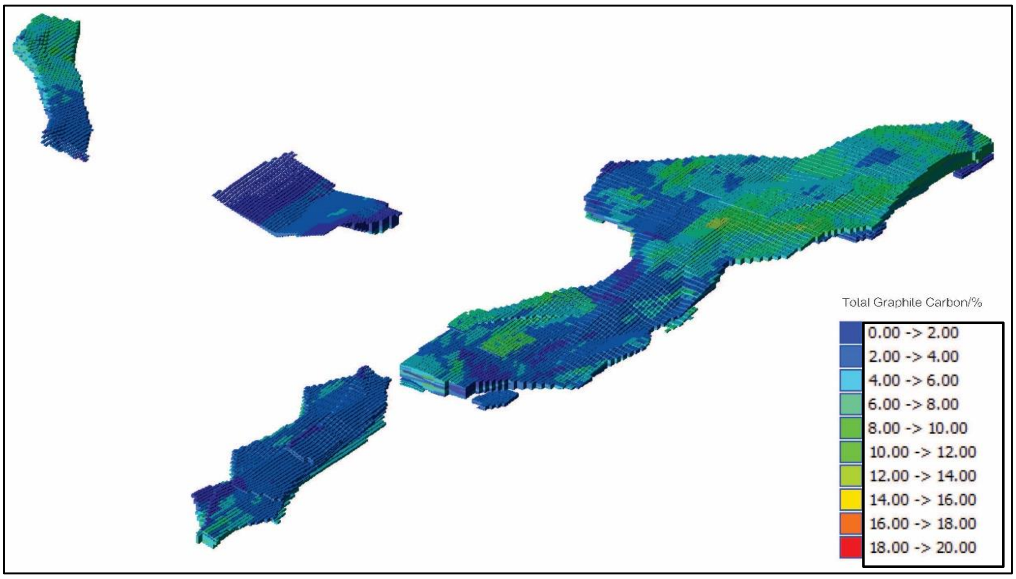

Fig.6 - Ore body model (colored by grade distribution)

Surpac software was used for resource estimation, the total amount of graphite ore was calculated to be 178 million tons and the total amount of graphite carbon was 10 million tons at the lowest industryl grade of 3.5%. At the same time, according to the calculation results of the resource, the Surpac software was used for statistics to obtain the tonnage and grade curves as below (Figure 7).

DOI 10.14311/CEJ.2018.04.0039

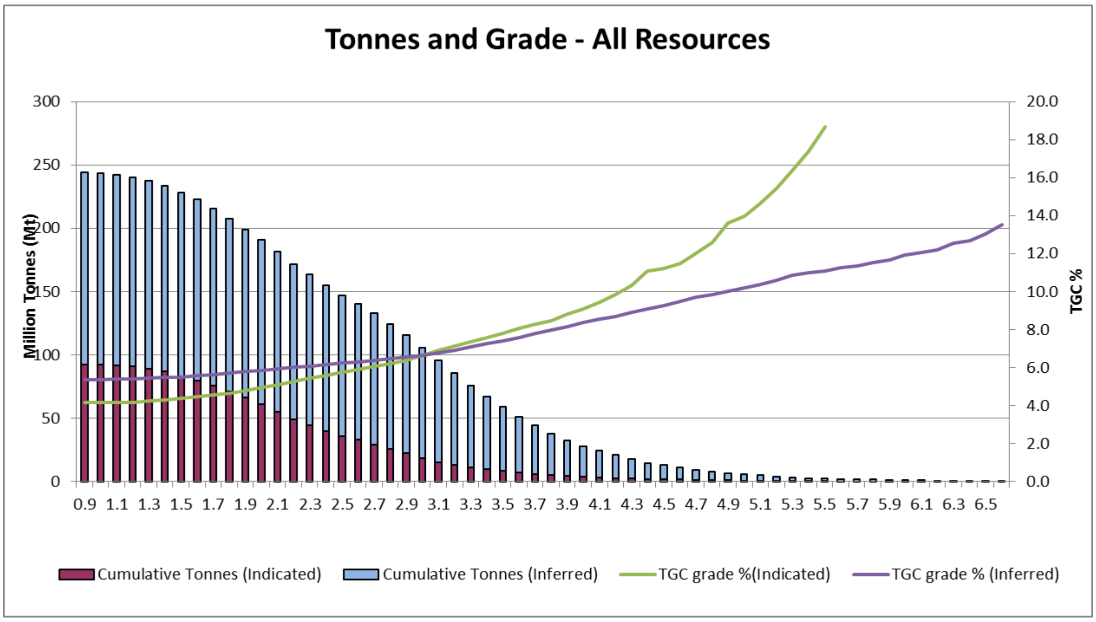

Fig.7 - Sujishan graphite ore grade tonnage map

It is noted that based on Figure 7 the total carbon ore and total graphite carbon ore are inversely related to the grades. According to the current market price and production operation cost, we can adjust the current indicators such as the ore grade and the selected grade in real time. Under different product market price conditions, the minimum mining industrial grade can be adjusted according to the tonnage-grade comparison chart to ensure the reasonability and orderly mining activity.

Comparing with the procedures of traditional resource estimation method which is normally called polygon method and direct geological interpolation are applied for all areas between sections, the geostatistical estimation of the resource process is more intuitive and reliable. Because of more delicate consideration of extension rules and local geological variability, the geostatistical estimation method can reflect the actual occurrence status of the deposit, and can effectively guide the production and exploration of the mine as well.

CONCLUSION

With using the theory of geostatistics, the author established the three-dimensional geological model of the Sujishan graphite mine by using Surpac software, and estimated the grade distribution of the ore body. At the same time, the experimental semi-variogram of the ore body striking, dipping and vertical directions were studied. The theoretical curve was fitted and the relevant estimation parameters were extracted. Finally, the total ore volume of the deposit was calculated to be 178 million tons and the total amount of graphite minerals is 10 million tons. Comparing with the traditional polygon estimation method, it is noted that the mine resource estimation by using the 3D geological software on the basis of the Kriging estimation method is more reasonable for the distribution of different grades of samples, and are closer to the actual mining situation of the mine. Meanwhile, the volume grade comparison table and the block model swats plots are applied to the block model validation, which verifies the rationality of the estimation method and results. Furthermore, in this paper, we analysed the grade tonnage curve of the mine, which provides further theoretical guidance for the selection of different minimum industry grades in the future exploration and production of the mine.

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