1 Introduction

For some old mines, their available mineral reservoirs are rapidly decreasing and even exhausting after decades of mining. However, there may be great mineral resource potentials in their depth and margin. Thus, techniques are required to prospect new mineral recourses in deep and marginal parts of the crisis mines.

With the maturing of geographical information system (GIS) techniques, the GIS-based mineral prediction and appraisal have becomes the mainstreams of the mineral resource appraisal regional resource prospectivity (Zhou et al., 2007; Carranza et al., 2008; Cassard et al., 2008). However, this line of researches only rely on 2D and 2.5D GIS, which are limited to the meet the requirement to prospect the mineral resources in 3D space, say, the deep and margin parts. On the other hand, since 1990s the techniques of 3D geological modeling (Houlding, 1994) have become more practical, which lays a solid foundation for generalizing the quantitative prediction of mineral resources to the 3D space.

This paper presents a novel method that adopts 3D geological modeling, 3D spatial analysis and visualization to achieve 3D quantitative mineral prospectivity. A case study from Fenghuangshan copper deposit, China was conducted, aiming at prospecting of mineral resources in the deep parts of the old and crisis mines.

2 Geology and Fenghuangshan Copper Metallogeny

The Fenghuangshan copper deposit locates in the Xinwuli basement, Fenghuangshan, Tongling district, China. The center of the basement is the Xinwuli pluton formed in late Yanshanian epoch, which consists of granodiorite and quartz monzodiorite. The strata around the basement are the carbonate rocks formed in Permian-Triassic ages. Currently discovered deposits distribute near and at the similar distance to the contact zone of the Xinwuli pluton, while no deposit is discovered in the pluton and the surrounding rocks far from the pluton. The NE trending fold-thrust system formed in Indo-Chinese epoch and keeping active during the magmatic emplacement in late Yanshanian epoch is the main structure controlling the locations of emplacement and mineralization.

Based on the above geological judgments, the factors controlling the distribution of the mineralization are abstracted to the ore-controlling (OC) fields as: (1) the thermal field $dG$ of the Xinwuli pluton, (2) the morphology of the Xinwuli pluton including the first undulation $wr1G$ and the second undulation $wr2G$ of the rock surface, (3) contact zone $dI$ of the Xinwuli pluton, (4) the structure of the contact face, that is, the angle $aIT$ between the original contact face and tendency contact face of the Xinwuli pluton, (5) lateral tension fault $dF$, (6) field of compression remote stress $aIP$ and (7) fold structures $dD3$.

3 3D Geological Modeling

The geological bodies in the Fenghuangshan copper deposit include the strata, structures, magmatic rocks and ore bodies. Since these geological bodies control the mineralization, in order to extract the metallogenic information, the geometric models of the geological bodies are constructed first. Here the Datamine Studio 3 is adopted to achieve the 3D geological modeling. First, the boundaries of the geological bodies on each cross section are delineated by importing the digitalized data of the exploration data and the prospecting lines. Next, the boundaries on different cross sections are connected, forming the wireframe models of the geological bodies.

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Finally, the wireframe models are converted to the block models, which facilitate the 3D spatial analysis for the extraction of OC fields.

4 Extraction of Metallogenic Information

The extraction of metallic information is based on the metallogenic law, aiming at obtaining the features correlated to the quality and quantity distribution of the mineralization. Here the main metallogenic information is abstracted to the OC information (e.g., geological condition of the magmatic rocks, structures and strata). In contrast, the signals of the other metallogenic information, such as clues from geophysical-geochemical anomalies, is relatively weak for the concealed ore bodies in crisis mines. Thus here the geophysical anomaly is only used to deduce the deep geometric information for the Xinwuli pluton.

OC fields. The OC fields listed in §2 that describe the intensity distribution of the OC processes are extracted via 3D spatial analysis approaches. Each OC field is represented by the 3D rasters, in which a voxel is a block of size 10m×10m×10m. Fig. 2 demonstrates the thermal field of Xinwuli pluton. Here the thermal field ($dG$) are associated with the distance to the pluton. Thus the field can be approximated by the distance field that can be computed efficiently via the 3D Euclidean transformation [Jones et al., 2006] to the block model of the Xinwuli pluton.

Correlation Analysis. After the OC fields are obtained, their correlations to the distributions of the mineralization are analyzed. The correlations are discovered by gathering known mineralized voxels and analyzing the corresponding scatter plots of the OC factors and the mineralized values, which are copper grade ($Cu$) and the copper tonnage ($CuOre$) respectively.

For example, from Fig. 3 it is observed that the relationships between $dG$ and $Cu/CuOre$ are nonlinear, formulated as:

$$
Cu = \beta_0 + \beta_1 ddG1 + \varepsilon
$$

$$
CuOre = \beta_{02} + \beta_{12} ddG2 + \varepsilon
$$

(1)

where $ddG1$ and $ddG2$ are the linearized variables related to the parameters $d1a$ and $d2a$ respectively:

$$
ddG1 = \begin{cases} 
|dG - d1a| & dG < 250 \\
|dG - d1b| & dG \geq 250
\end{cases}
$$

$$
ddG2 = \begin{cases} 
|dG - d2a| & dG < 250 \\
|dG - d2b| & dG \geq 250
\end{cases}
$$

By solving the nonlinear regression in the form of Eq. (1) the relationships among the variables are gained, via which the OC factors are converted to OC indicators to
indicate the mineralization favorableness. 

To further find the correlations between OC indicators and the mineralized values, all of the OC indicators are integrated into a joint relationship to the mineralized values. Since the OC indicators are linearized to the mineralized values in the spirit of Eq. (1), this relationship is formulated as the form of multivariate linear regression:

\[ MV_k = B_{k0} + \sum_{j=1}^{p} B_{kj} GV_j + \epsilon, k = 1, \ldots, m \]

(2)

where \( MV_k \) denotes the mineralized values (Cu and CuOre), \( GV_j \) denotes the OC indicators (e.g., \( ddG1 \) and \( ddG2 \)), \( \epsilon \) is the random variable of zero expected value, and \( BK_0 \) and \( BK_i \) are the parameters to solve. For the Fenghuangshan ore field, all \( GV_j \) have significant linear correlation with \( MV_k \), and the Eq. (2) is also significant in the F-test: \( F(7,2557)=71.75604513722, F_{0.05}(7,2557)=2.01 \).

5 Visualization of Predictivity Results

Using the predictivity model in Eq. (2), the predicted mineralized values for the voxels in the unknown region are gained. By summing up the mineralized voxels, the undiscovered concealed ore bodies and the predicted copper grade (ECu) and tonnage (ECuOre) are gained. Fig. 4 shows the visualization of the predictivity results.

According to the predictivity results, deep prospecting engineering is designed, which includes 27 predictivity planar maps, 5 cross sections, 54 predictivity contour maps. Besides, 4 three-dimensional target areas for deep prospecting were delineated.

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References


