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Quantitative analysis of intrusive body morphology and its relationship with skarn mineralization—A case study of Fenghuangshan copper deposit, Tongling, Anhui, China

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Abstract: The shapes of intrusive body and contact zone might influence the formation and distribution of orebodies in skarn deposit. By taking Xinwuli intrusive body in Fenghuangshan copper deposit, Tongling, Anhui, China, as the research object, a new method was used to obtain the quantitative relationship between intrusion morphology and skarn mineralization. The first step of the method was to extract morphological characteristic parameters based on mathematical morphology and Euclidean distance transformation; then the quantitative relationship between the parameters and orebodies was analyzed; finally correlational analyses between the parameters and mineralization indices were conducted. The results show that morphological characteristic parameters can effectively indicate the location of concealed ore bodies in skarn deposit, with the following parts as advantageous positions of skarn mineralization: (1) the parts away from the 1st trend surface in the range from −25 to 50 m; (2) the convex parts about 200 m away from the 2nd trend surface, around which the tangent plane of the intrusive body is approximately consistent with the trend surface; (3) the contact zones with angle between intrusive body original contact surface and trend contact surface ranging from 35° to 70°; (4) the parts with angle between intrusive body original contact surface and regional extruding far crustal stress ranging from 50° to 60°. These knowledge can be applied to more skarn deposits for future mineral exploration.

Key words: intrusive body morphological analysis; contact zone; mathematical morphology; skarn mineralization; Fenghuangshan copper deposit

1 Introduction

Skarn deposit has important industrial values, which is the main deposit type of rich copper deposit, rich iron deposit, tungsten deposit and tin deposit in China. The formation mechanism of skarn deposit is surrounding rock replaced by magmatic hydrothermal liquid, so the composition, formation depth, shape and scale of intrusive body have a decisive influence on the formation of skarn deposit. As the concavo−convex interface is more conducive than the smooth interface for mineralization, the shape of intrusion has certain effect on the formation and distribution of skarns and ore bodies. According to literature, the recessed parts of the intrusive body are more advantageous for mineralization than the protruding parts [1]. Thus, it is meaningful to study the occurrence and shape of the lower portion of intrusive body in the areas which have good metallogenic prospects [2]. The formation and distribution of orebody have close relationship with the complexity of the granite surface shape [3].

The skarn deposit is also controlled by contact zone between intermediate-acidic intrusive rocks and carbonate rocks [4,5]. Thus, the shape of contact zone plays an important role in metallogenic prognosis, as the more complex the contact structure morphology is, the more conducive to the mineralization [6].

In summary, analysis of the shape of intrusive body and contact zone is significant for metallogenic prognosis, exploration and exploitation of skarn deposit. However, previous studies dealing with morphology analysis are mainly based on 2D cross section maps, and the conclusions are drawn empirically by observing and comparing the relationship between the orebodies and the shape of intrusive bodies and contact zone. Many

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scholars have achieved the 3D simulation and morphological description of intrusive body and contact zone by using 3D software, and discussed the relationship between their shape and the spatial location of orebody [5,7,8]. But, the 3D quantitative morphology analysis of intrusive body and contact zone is not realized, which is not conducive for revealing the ore-controlling regularity.

Fenghuangshan copper deposit is one of the important copper deposits of Yangtze River metallogenic belt [9,10]. Many scholars believe that Fenghuangshan copper deposit is a typical skarn copper deposit after analyzing its geological characteristics, mineralization, mineralization stage and sources of metallogenic material [11,12]. Taking Xinwuli intrusive body in Fenghuangshan copper deposit as research objective, using mathematical morphology [13,14] and Euclidean distance transformation [15,16], the authors put forward a 3D morphological analysis method for intrusive body shape based on 3D raster model [17], including the hierarchical extracting and quantitative analysis of the characteristics of morphology undulance, and the geometric parameters extraction of intrusive body surface used to measure the 3D morphological features.

2 Quantitative morphological analysis method of intrusive body

Geologic bodies are discontinuous spatial entities in geological space, including sedimentary rock, intrusive body and deformation structure [18]. 3D geological model can visually demonstrate and describe the geometry and spatial distribution of geological bodies. On the basis of 3D model of the intrusive body in skarn deposit, 3D spatial analysis techniques can be used for analyzing surface morphological undulance, quantitatively extracting its geometric morphological parameters and achieving the quantification of ore-controlling indicators of intrusive body shape.

2.1 Intrusive body morphology modeling

3D geological modeling is important for understanding geological settings and spatial analysis. Considering the characteristics of spatial data model and purpose of the study, the geological body surface model based on surface representation will be firstly established, and then converted into 3D raster model based on body representation.

Based on three-dimensional computer image reconstruction technology, by combining the geological experiences, geological data and 3D modeling software, the rock borders can be delineated in 3D space by human−computer interaction, then we can generate the wireframe model and the raster model of intrusive body with the rock borders, and finally demonstrate them on the computer in order to analyze intrusive body shape.

3D structure raster model of intrusive body can be used for observation of its spatial morphology in multi-angle, and makes it easier for intuitive understanding and analysis of the internal structure and the space attribute distribution.

2.2 Intrusive body surface morphological undulance analysis

The morphological characteristics of intrusive body are important for mineralization in skarn deposit. The quantitative analysis of intrusive body surface morphological structure helps to reveal the spatial mineralization location regularity. The method of combining Trend and Remainder Analysis and structural analysis can be used for multi-level decomposition and geometrical modeling of geological body morphological undulance [19], but this method is not suitable for a complicated geologic body.

By using mathematical morphology and Euclidean distance transformation, the authors put forward 3D morphological analysis method for intrusive body shape based on 3D raster model [20]. Firstly, a spherical structure element of a certain radius is used to do morphological filtering for intrusive body in order to obtain trend morphology. Then, trend morphology set is divided, which is obtained through set operations from intrusive body voxels set, into convex peak part and concave valley part. Finally, Euclidean distance field is built in 3D space by Euclidean distance transform to measure based on trend morphology, and then the distance from voxel is obtained in the set of convex part and concave part to trend morphology outline. The local concave degree and convex degree of intrusive body surface can be quantitatively expressed by it.

Because the radius of spherical structure element decides the size of filtering-out waveform, using different radius values can extract different degrees of undulance.

2.3 Morphological parameter extraction

The shape and distribution of orebody in skarn deposit are also controlled by contact zone and related fracture, specifically manifested by the size of angle between interfaces of geologic bodies. In order to quantitatively express these ore-controlling factors, the angle between the contact surface and the trend surface as well as the angle between the contact surface and the regional stress field need to be extracted. Geologic bodies are discretely expressed in voxel raster model. The extraction issue of the angle is specified into an issue to solve the angle between tangent planes of two voxels corresponding to two spatial entities. Dealing with extraction of angle parameter, the author puts forward a method based on the Euclidean distance field.

As shown in Fig. 1, there is a voxel v on the surface of the geologic body (solid line) and its nearest voxel on the surface of the trend shape of the geologic body (dotted line) is v'. Then, the angle θ between the tangent planes passing through the two voxels can be worked out through the angle θ' between the normal vectors of the two voxels.

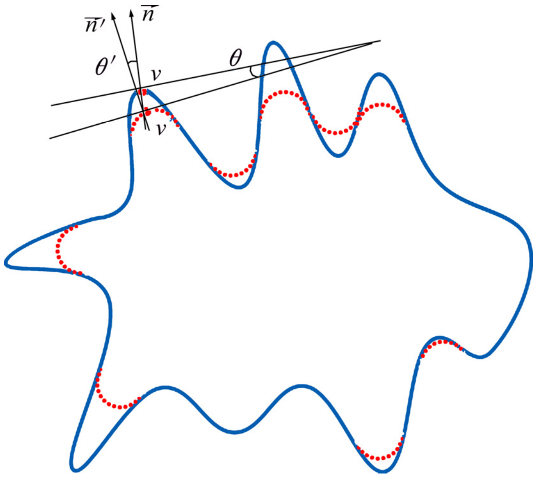

Fig. 1 Angle between two contact surfaces

The followings are specific steps to find angle parameter.

1) Use method mentioned in Section 2.2 to extract the original contact surface and the trend contact surface of geologic body.

2) Work out the inside and outside Euclidean distance fields corresponding to the two surfaces.

3) Do convolution operations to distance fields by using gradient operator in order to obtain the normal vectors corresponding to the two surfaces.

4) Work out the angle parameter θ between two tangent planes as follows:

$$\theta = \arccos\left(\frac{\vec{n}\cdot\vec{n}'}{\|\vec{n}\|\ \|\vec{n}'\|}\right)$$

3 Intrusive body morphological analysis and its relationship with skarn mineralization of Fenghuangshan copper deposit

Fenghuangshan copper deposit is a typical skarn copper deposit. The Xinwuli intrusive body in Fenghuangshan copper deposit has a wide range of overlap phenomenon, so the Trend and Remainder Analysis method cannot be used for its morphology analysis. Taking Xinwuli intrusive body as research objective, using mathematical morphology and Euclidean distance transformation, we put forward a 3D morphological analysis method for intrusive body morphology based on 3D raster model. This method can quantitatively extract and analyze geometry features and morphological parameters of Xinwuli intrusive body, quantitatively analyze and describe the relationship between intrusive body morphological parameters and the spatial distribution of mineralization, and thus reveal the ore-controlling regularity of the shape of intrusive body.

3.1 Geological characteristics of intrusive body in Fenghuangshan copper deposit

The Fenghuangshan copper deposit is located in the Xinwuli basin, approximately 35 km southeast of Tongling city, Anhui Province, China. As the main intrusion of the 12 outcroppings with an outcrop area of 10 km^2 in Fenghuangshan mine, the Xinwuli intrusive body, formed in the late Yanshan period, outputs in the core of the Fenghuangshan syncline occurring as a stock. It has an intrusive contact relationship with the Middle Triassic limestone. The developed structural system and the magmatism process, in which the rock body is formed from different intrusions by granitoid magma, lead to the intrusive and the contact zone tectonics with complex shape.

The main orebody was formed in the contact zone between diorite and Middle Triassic limestone, and its shape appears to be lenticular and platy-like. It is controlled by the formation condition, intrusive bodies and structures.

The ores are not consistent with the content of ore-forming elements in the formation; however, they are controlled by hydrothermal mineralization that are closely associated with the favorable formation, such as the broken limestone.

The magmatic intrusions, which are the important ore-controlling factors, consist mainly of granodiorite, quartz monzonite, monzogabbro, and quartz monzodiorite. The contact zone provides the essential space for the Cu mineralization. The Xinwuli intrusion is the product of different intrusions by granitoid magma; besides, the main ore forming process took place in the early time and the late magmatism enriched the early ores.

The main structures in Fenghuangshan copper deposit are contact zone tectonic and fault structure. The contact zone tectonic is the important ore-controlling factor, for the main ores are located in the west contact zone of Xinwuli intrusive body [10]. According to the geology data, the ore-hosted situations about the main deposits are closely related to the contact zone, the overlap of intrusions, the dent of intrusion’s top or sides, contact surface with complex shape, the broken contact zone, and somewhere the content of xenoliths is high.

But, not all contact zones have ore outputs, and the fault structure is also an important factor for ores distribution. When the fault dips to the intrusive body (east), the position is favorable for Cu mineralization, and when the fault dips to the surrounding rock, it is opposite.

3.2 Intrusive body morphological analysis

3.2.1 3D modeling of Xinwuli intrusive body

We have collected 420 drillhole data, 71 cross-sections, DEM data and other geological data from the Fenghuangshan copper deposit, which are used to establish the 3D model of Xinwuli intrusive body.

The following are specific steps to build the 3D geological model of Xinwuli intrusive body.

1) Extract the geological modeling data, including the collection and collation of related original data, the vectorization of related geological maps, and establishment of comprehensive geological database.

2) Import geological modeling data to 3D modeling software.

3) 3D display of individual projects and prospecting line profile maps.

4) Build intrusive body wireframe model by human−computer interaction.

5) Build intrusive body block model.

The wireframe model is described by triangle and vertex files, and the block model is described by the prototype table file and model table file.

Figure 2 shows the three-dimensional raster model of Xinwuli intrusive body.

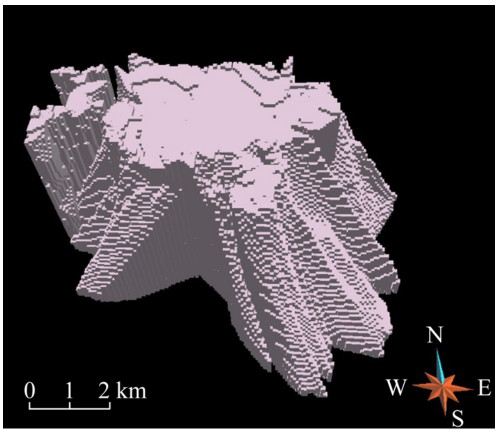

Fig. 2 Three-dimensional raster model of Xinwuli magmatic body

3.2.2 Morphological undulance analysis of Xinwuli intrusive body

The morphological characteristics of Xinwuli intrusive body control the formation, location and distribution of orebody. Surface morphological undulance extraction method is used for analyzing this ore-controlling factor. The spherical structure element was used with the radius of 100 and 1000 m and the two-grade morphological undulance analysis was made. Figure 3 shows the 1st- and 2nd-level intrusive body's trend model. Morphological factors w_{r1G} and w_{r2G} represent the degree of the 1st- and 2nd-level undulance on the rock surface, respectively. The minimum Euclidian distance between voxel and trend part of intrusive body voxel is used to make the calculation. Obviously, if intrusive body voxel belongs to the convex part in corresponding level undulance, the value of w_{r1G} and w_{r2G} is greater than 0, and when intrusive body voxel belongs to the concave part, the value of w_{r1G} and w_{r2G} is smaller than 0.

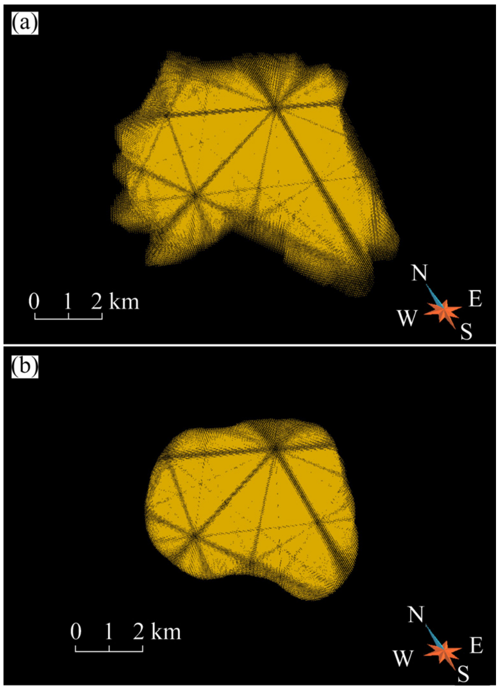

Fig. 3 Morphological undulance analysis on Xinwuli intrusive body: (a) 1st-level trend model, (b) 2nd-level trend model

3.2.3 Morphological parameter extraction of Xinwuli intrusive body

According to orebody location pattern of Fenghuangshan copper deposit, orebody distribution is controlled by contact zone and the expansion space along it. The angle parameter a_{IT} between the original contact surface and the trend contact surface of intrusive body can be used to express the controlling function.

The mineralized fracture controlling the distribution of Fenghuangshan copper deposit copper body has northwestern specificity obviously, and this kind of specificity is concerned with regional crustal stress field. The angle parameter a_{IP} between regional crustal stress direction surface and Xinwuli intrusive body original interface is used to express this controlling function. For any unit in geological space, its angle parameter between extruding crustal stress direction surface and original interface is the value of the nearest unit at interface.

3.3 Relationship between intrusive body shape and skarn mineralization

For three-dimensional quantitative prediction of concealed orebody, it is necessary to quantitatively express ore-controlling factors, and grasp the quantitative relationship between the mineralization distribution and ore-controlling geological factors. To achieve the quantitative expression of ore-controlling geological factor indicators, the concept of ore-controlling geological factor field was put forward [21], which reflects the result and distribution of ore-controlling geological processes in geological space. To improve the accuracy of analysis and expression, a 50 m × 50 m × 50 m raster model is used to describe the ore-controlling geological factor field.

According to orebody location pattern of Fenghuangshan copper deposit, the raster models of Xinwuli intrusive body, its morphological undulance field models and the contact zone morphological parameter field models are built by the new method. After obtaining the quantitative relationship between orebody and morphological characteristics of the intrusive body, the ore-controlling geological factor fields, unit mineralization index copper (C), and copper metal (C_{Ore}) relational model are established with a statistical analysis method in order to achieve quantitative effect of intrusive body morphology on the orebody.

3.3.1 Relationship between morphological factor w_{r1G} and skarn mineralization

The sophisticated morphological undulance of rock surface can be extracted by using smaller radius of spherical structure element. Morphological factor w_{r1G} of intrusive body represents the degree of the 1st-level undulance on the rock surface.

We search for the relationship between morphological factor w_{r1G} and mineralization by overlaying orebody raster model with 1st-level convex parts and 1st-level concave parts of intrusive body (Fig. 4(a)). As shown in Fig. 4(a), the red blocks are orebody raster model, the yellow point cloud is the 1st-level convex part and the blue point cloud is the 1st -level concave part. We can find that, the main orebody of Fenghuangshan copper deposit occurs with arc-shape in contact zones between the top of Xinwuli intrusive body and surrounding rock. The morphology of intrusive body besides mineralization place is the irregularities site linked with convex parts and concave parts, i.e., the overlap bodies of upper rock body or the convex parts whose lower edge portion is concave or continuous undulance. For further quantitative analysis, we overlap orebody raster model (red blocks) with w_{r1G} field model (Fig. 4(b)), then find that orebodies mainly occur beside the white and light orange area of w_{r1G} field model, i.e., the parts of intrusive body away from the 1st trend surface in the range from −25 to 50 m, and a small amount of orebodies are located beside the green area, i.e., the parts away from the 1st trend surface in the range from −100 to −25 m.

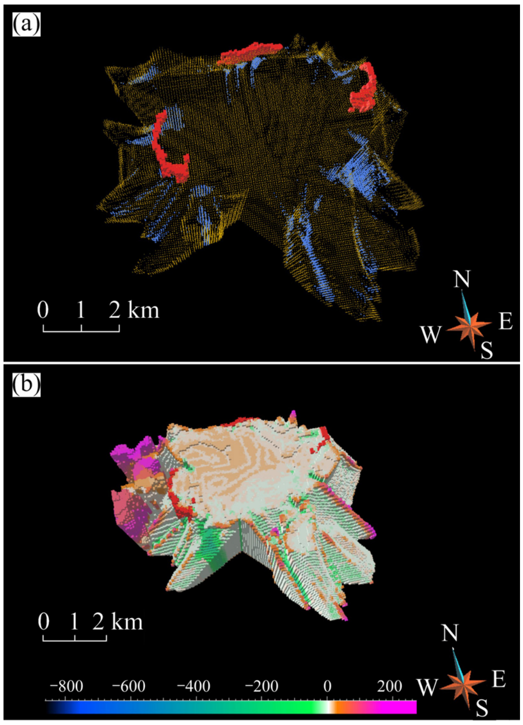

Fig. 4 Relationship between intrusive body morphological 1st-level undulance and orebody: (a) 1st-level convex and concave parts and orebody raster model; (b) Morphological factor (w_{r1G}) raster model and orebody raster model

The scatter diagram of w_{r1G}–C and w_{r1G}–C_{Ore} (Fig. 5) shows that the values of mineralization indexes C and C_{Ore} mainly occur in the units with w_{r1G} value ranging from −90 to 50, which are located in the main mineralization enrichment space, and the units with w_{r1G} value ranging from −20 to 20 have obvious higher C and C_{Ore} values. The optimal mineralization sites are the units with w_{r1G} value near zero. The units with w_{r1G} value greater than 50 and less than −90 have obvious lower C and C_{Ore} values, which are non-ore or lean ore spaces.

Overall, we find that the orebody emplacement in the 1st-level undulation has the following rules: the most advantageous position of orebodies lies in the rock upper contact zone, where the tangent plane of the intrusive body is approximately consistent with trend surface, and rock contact surface has continuous undulance (in every direction). Combining geologic features with metallogenic theory, we believe that the main reason for orebody emplacement is the variation of thermodynamic field. As the intrusion of the Xingwuli intrusive body,

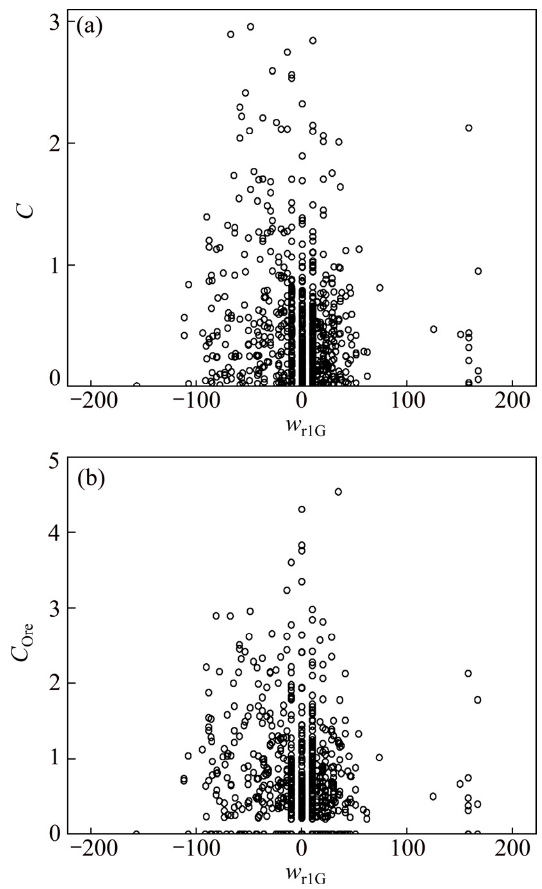

Fig. 5 Scatter diagrams of w_{r1G}−C (a) and w_{r1G}−C_{Ore} (b)

orebody was often located in tectonic weak zones, and thus complex shape occurred at the top of the intrusive body. Moreover, the stress at the top of intrusive body is most concentrated, and the surrounding rock around it is slice argillaceous limestone. In addition to the stress and heat, theomorphic fold and ductile shearing occur. The subsequent condensation of the rock changes the compression stress field to extension stress field. All of these form series of contracted space parallel to the intrusive body, the size of which is closely related to the contact range of rock and surrounding rock. When the rock overlap or semi-encompassed the surrounding rock, the space is the largest.

Previous research shows that the precipitation of main orebody occurs after the large scale silicon lithification at the Fenghuangshan copper deposits [10]. ZHANG [22] also points out that the second boiling which has important relationship with mineralization occurs in quartz sulfide stage, so water−rock reaction is not the main cause of ore precipitation. The boiling action of hydrothermal and the mixing action of two kinds of fluid are the main cause of metallogenic [22,23]. After the intrusion of magma, due to the low viscosity [24], magmatic hydrothermal fluid is concentrated on the upper boundary layer of magma in relatively high concentration. The ore flows in the magma system driven by magma thermal stress and fluid pressure [25]. In the process of rock condensation, fluid drainage produces hydraulic fracturing on the surrounding rock, which has interaction with the change of stress field. All of these form the important metallogenic space, which shows the consistency of dilatancy and confluence [10,26], and is called dilatancy confluence space. There is rich magmatic hydrothermal fluid, which has strong negotiability with the outsides, and the lithology has huge difference on both sides of the wall rock, so it is a kind of typical edge of chaos. The area that has obvious changes in the physical and chemical conditions is considered the most favorable mineralization position [27,28]. Dilatancy confluence space is controlled by many factors. The tectonic stress field at the concave and convex parts between the rock and surrounding rock has the most intense change, which forms a low-pressure space changing the original fluid field (improving the migration rate of the fluid and changing its direction). Thus, it forms dilatancy confluence space, and orebody is located here.

Obviously, the relationship between indexes C, C_{Ore} and w_{r1G} is nonlinear, so the nonlinear models must be established to simulate them, and we can get two new indexes d_{r1G1} and d_{r1G2}. We calculate C/d_{r1G1} and C_{Ore}/d_{r1G2} correlation coefficient and use F-test to analyze the significant relationship between them. The results are given in Table 1.

From Table 1, significant linear correlations were observed between mineralization indexes C, C_{Ore} and variables d_{r1G1}, d_{r1G2} respectively, i.e., d_{r1G1} and d_{r1G2} have significant contributions to or significant controlling effects on mineralization spatial distribution, and they can be used as ore-controlling indexes to indicate the favorable mineralization degree of geological factors.

3.3.2 Relationship between morphological factor w_{r2G} and skarn mineralization

The 2nd-level intrusive body morphological undulance is extracted on the basis of the 1st-level trend

Table 1 Correlation coefficient and regression effectiveness of mineralization indexes C and C_{Ore} with intrusive body morphological undulance variable d_{r1G1}, d_{r1G2}

Regression model	Correlation coefficient, R	$F(1, 2557)$	$F_{0.05}(1, 2557)$	Regression effect
$C=b_0+b_1d_{r1G1}+\varepsilon$	−0.1756	81.8925	3.8451	Significant
$C_{Ore}=b_0+b_1d_{r1G2}+\varepsilon$	−0.1401	51.5481	3.8451	Significant

shape by using larger radius of spherical structure element, which ignores the small change of rock surface undulance, and reflects the overall change of rock surface morphology. Therefore, the 2nd-level intrusive body morphological undulance can integrally reflect the interaction between intrusive body and geological space. Morphological factors w_{r2G} of intrusive body represent the degree of the 2nd-level undulance on the rock surface.

Figure 6(a) shows the results obtained by overlaying orebody raster model with 2nd-level convex parts and 2nd-level concave parts of intrusive body. In Fig. 6(a), the red blocks represent orebody raster model, the yellow point cloud is the 1st-level convex part and the blue point cloud is the 1st-level concave part. We can find that the main orebody of Fenghuangshan copper deposit occurs in contact zones between the top of Xinwuli intrusive body and surrounding rock with arc-shape. The intrusive body besides orebody belongs to the 2nd-level convex parts in horizontal direction, and the convex parts of the irregularities linked site of the 2nd-level undulance in vertical direction have the consistent strike with intrusive body trend surface. For further quantitative analysis, after overlying orebody raster model (red blocks) and w_{r2G} field model (Fig. 6(b)), we can find that orebody mainly occurs beside the pink areas of w_{r2G} field model, which are the parts of intrusive body away from the 2nd trend surface in the range of 30−300 m. The common

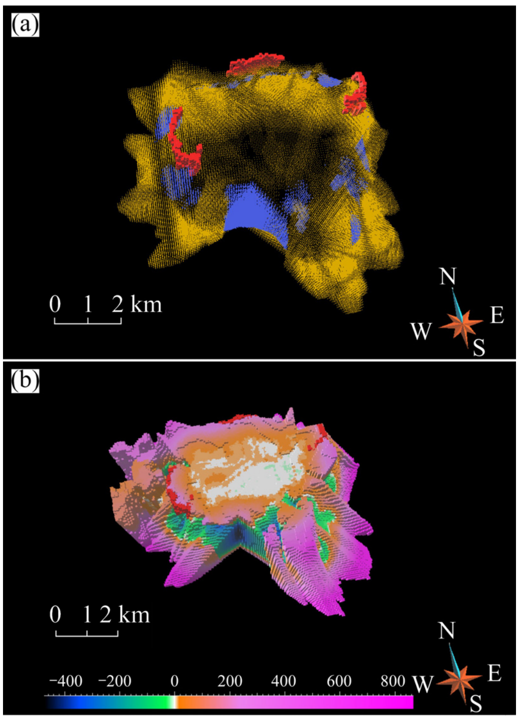

Fig. 6 Relationship between intrusive body morphological 2nd-level undulance and orebody: (a) 2nd-level convex and concave parts and orebody raster model; (b) Morphological factor (w_{r2G}) raster model and orebody raster model

features of these parts are: intrusive body has larger undulance; it has the light blue area (200+) representing convex and light yellow area (20+) representing that intrusive body is approximately consistent with trend surface.

The scatter diagram of w_{r2G}−C and w_{r2G}−C_{Ore} (Fig. 7) shows that the values of mineralization indexes C and C_{Ore} mainly occur in the units with w_{r2G} value in the range from −150 to 300, which are located in the main mineralization enrichment space. The units with w_{r2G} value ranging from 0 to 250 have obvious higher C and C_{Ore} values, and the optimal mineralization sites are the units with w_{r1G} value in the range of 100−200. The units with w_{r1G} value larger than 300 and less than −150 have obvious lower C and C_{Ore} values, which are located in non-ore or lean ore space.

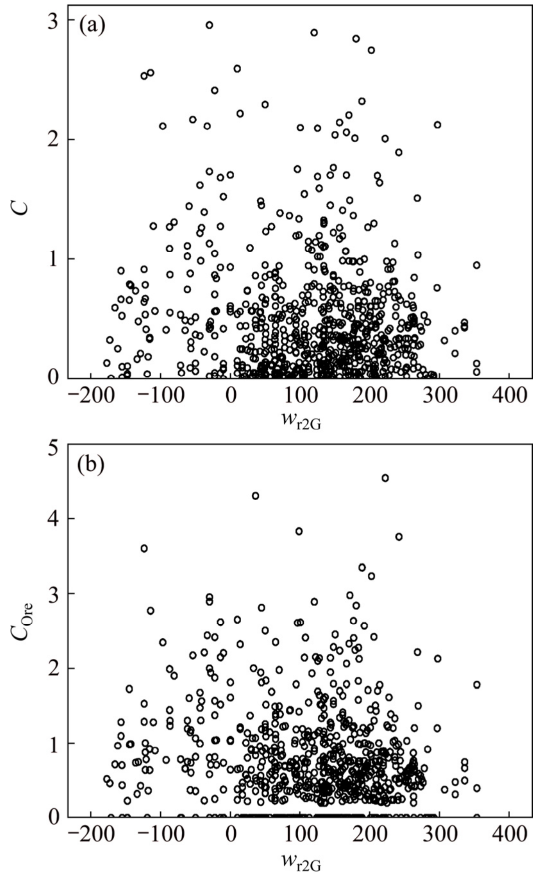

Fig. 7 Scatter diagrams of w_{r2G}−C (a) and w_{r2G}−C_{Ore} (b)

Overall, we find that the orebody emplacement in the 2nd-level undulation has following rules: the most advantageous position of orebody lies in the convex contact zones where the 2nd-level (or even higher level) concave and convex zones develop. In contrast to the connection part of concave and convex zones in the 1st-level undulation of intrusive body, there is difference in the 2nd-level undulation that the most advantageous position of orebodies lies in the convex part combined-controlled by the local concave and convex zones. The variation here reflects the importance of local activation to mineralization [27,28]. Due to the balloon inflated active emplacement of magmatic emplacement at shallow deposits [11], the differences among surrounding rocks, heterogeneities of tectonic stress fields as well as the varieties of thermal force fields, a series of combination undulation areas of concave and convex zones form at the top of the rock. Moreover, Xingwuli intrusive body is formed by multiphase magmatism. Because of the continuous stability of multiphase intrusive body intrusion and the geological space effect, the orebodies are more likely to locate here. As mentioned above, magmatic hydrothermal fluid is always at a high concentration in magma under the upper boundary layer, and it is possible to exist a collecting area of hydrothermal fluid in the convex zones of rock. When fluids release, a strong exchange of volume leads to the breaking of surrounding rock, which also affects the original shape of rock, thus leading to the ore formation in confluence area.

As there is a linear relationship between indexes C, C_{Ore} and w_{r2G}, we directly calculate C, C_{Ore} and w_{r2G} correlation coefficient and use F-test to analyze the significant relationship between them. The results are given in Table 2.

Table 2 Correlation coefficient and regression effectiveness of mineralization indexes C and C_{Ore} with intrusive body morphological undulance variable w_{r2G}

Regression model	Correlation	$F(1, 2557)$
$C=b_0+b_1w_{\mathrm{r2G}}+\varepsilon$	−0.2265	139.2295
$C_{\mathrm{Ore}}=b_0+b_1w_{\mathrm{r2G}}+\varepsilon$	−0.1626	69.9079

Regression model	$F_{0.05}(1, 2557)$	Regression effect
$C=b_0+b_1w_{\mathrm{r2G}}+\varepsilon$	3.8451	Significant
$C_{\mathrm{Ore}}=b_0+b_1w_{\mathrm{r2G}}+\varepsilon$	3.8451	Significant

From Table 2, significant linear correlations are observed between mineralization indexes C, C_{Ore} and variable w_{r2G}, i.e., w_{r2G} has a significant contribution to or significant controlling effect on mineralization spatial distribution, and it can be used as ore-controlling index to indicate the favorable mineralization degree of geological factors.

3.3.3 Relationship between contact surface structure factor a_{IT} and skarn mineralization

Interface structures are located in the first interaction zone between intrusive body and surrounding rock, and the extrusion stress and extensive stress make the contact zone broken in the process of intrusive body invading surrounding rock. The expansion space is formed during this process, which is beneficial to circulation function of magmatic hydrothermal fluid and meteoric water. Contact surface structure factor a_{IT} indicates the expansion space distribution and force condition in rock contact zone.

Overlaying orebody raster model (red blocks) with a_{IT} field model (Fig. 8), we can find that orebodies mainly occur beside the blue and light blue areas of a_{IT} field model, i.e., the parts of intrusive body have the a_{IT} value in the range of 35−70, and a small amount of orebodies are located beside the green area, i.e., the parts of intrusive body have the a_{IT} value in the range of 10−35.

The scatter diagram of a_{IT}−C and a_{IT}−C_{Ore} (Fig. 9) shows that the values of mineralization indexes C and C_{Ore} mainly occur in the units with a_{IT} value in the range of 0−100, which are located in the main mineralization

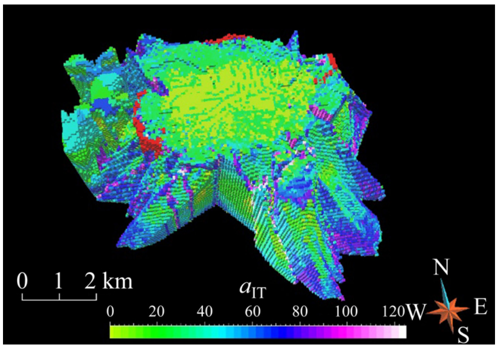

Fig. 8 Raster models of contact structural factor (a_{IT}) and orebody

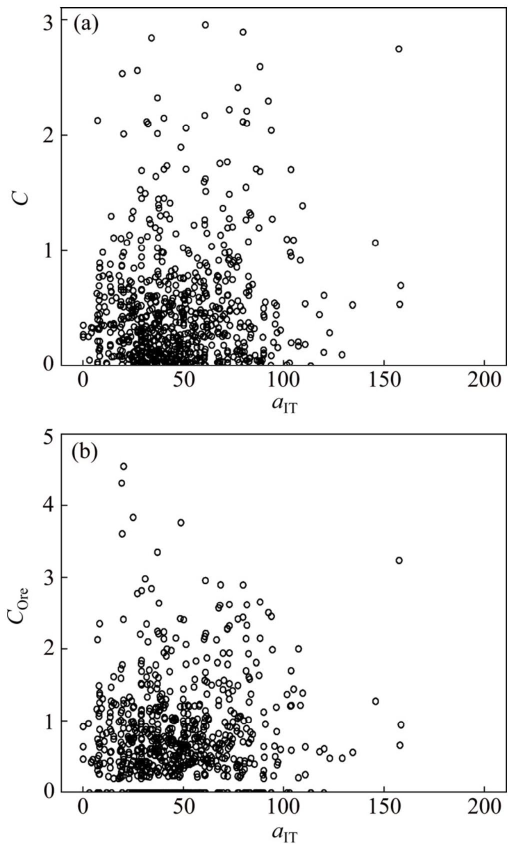

Fig. 9 Scatter diagrams of a_{IT}−C (a) and a_{IT}−C_{Ore} (b)

enrichment space, and the units with a_{IT} value in the range of 10−70 have obvious higher C and C_{Ore} values, and the optimal mineralization sites are located in the units with a_{IT} value in the range of 40−60. The units with a_{IT} value larger than 100 have obvious lower C and C_{Ore} values, which are located in non-ore or lean ore space.

Through comprehensive analysis, we find that the orebody emplacement in the contact surface structure has the following rules: the parts with a_{IT} value in the range of 35−70 are located in the favorable place for orebodies emplacement, i.e., the areas link the convex parts and concave parts of contact zone, with its convex parts near the left part and the small and uniform surface undulance degree. LIU et al [10] conclude the regularity of contact zone ore-control, and believes that the contact zones develop tensional faulted structures with parallel occurrence, which shows that not only magmatic hydrothermal fluid but also tectonic deformation is closely related to orebody formation in contact zone. In this work, the parts linking the convex parts and concave parts of contact zone are in extension environment because of the extrusion force in the process of intrusive body invading surrounding rock according to the geological mechanics, and these sections are located in the structural weak surface which can produce tensional faults combining the inherited extension in the process of rock solidification contraction and regional stress field.

As there is a linear relationship between indexes C, C_{Ore} and a_{IT}, we directly calculate C, C_{Ore} and a_{IT} correlation coefficient and use F-test to analyze the significant relationship between them, and the results are given in Table 3.

Table 3 Correlation coefficient and regression effectiveness of mineralization indexes C and C_{Ore} with contact surface variable a_{IT}

Regression model	Correlation	$F(1, 2557)$
$C=b_0+b_1a_{IT}+\varepsilon$	0.2236	135.5590
$C_{Ore}=b_0+b_1a_{IT}+\varepsilon$	0.2353	150.9435
Regression model	$F_{0.05}(1, 2557)$	Regression effect
$C=b_0+b_1a_{IT}+\varepsilon$	3.8451	Significant
$C_{Ore}=b_0+b_1a_{IT}+\varepsilon$	3.8451	Significant

From Table 3, significant linear correlations are observed between mineralization indexes C, C_{Ore} and variable a_{IT}, i.e., a_{IT} has a significant contribution to or significant controlling effect on mineralization spatial distribution, and it can be used as ore-controlling index to indicate the favorable mineralization degree of geological factors.

3.3.4 Relationship between regional extruding far crustal stress field factor a_{IP} and skarn mineralization

The effects of regional extruding far crustal stress field on orebody location are reflected through macroscopic controlling on geological spaces.

Overlaying orebody raster model (the red blocks) with a_{IP} field model (Fig. 10), we can find that orebodies mainly occur beside the blue and light blue areas of a_{IP} field model, i.e., the parts of intrusive body have the a_{IP} value in the range of 60−120, and a small amount of orebodies are located beside the green and pink area, i.e., the parts of intrusive body have the a_{IP} value in the range of 30−60 and 120−160.

The scatter diagrams of a_{IP}−C and a_{IP}−C_{Ore} (Fig. 11) show that the values of mineralization indexes

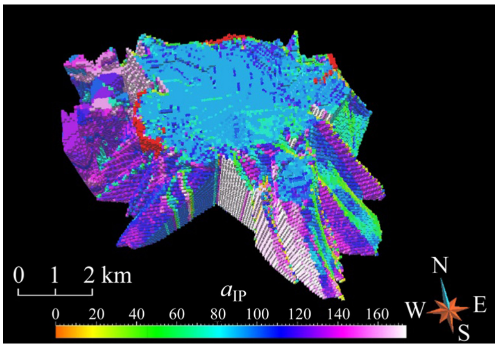

Fig. 10 Raster models of regional extruding far crustal stress field factor (a_{IP}) and orebody

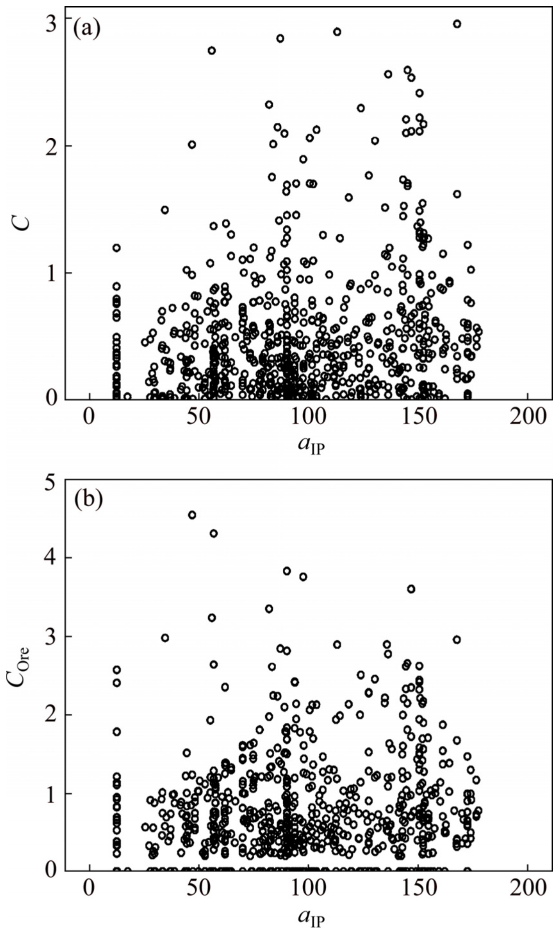

Fig. 11 Scatter diagrams of a_{IP}−C (a) and a_{IP}−C_{Ore} (b)

C and C_{Ore} mainly occur in the units with a_{IT} value in the range of 30−160. The units with a_{IP} value in the range of 50−100 have obviously higher C and C_{Ore} values, which are located in the main mineralization enrichment space, and the units with a_{IP} value in the range of 140−160 have relatively high C and C_{Ore} values, which are located in the secondary mineralization enrichment space.

Overall, we find that the locations of orebodies in regional extruding far crustal stress field factor have the following rules: the most advantageous position of orebodies lies in the parts where their a_{IP} value is in the range of 50−60, i.e., the parts where rock contact zone and regional extruding far crustal stress field cross at moderate or high angle. The mineralization of Fenghuangshan copper deposit is controlled by regional and local stress field. The local abnormality is the favorable condition for deposit, and the local stress field has a close relationship with the magmatic metallogenic system [29]. As mentioned before, orebodies are controlled by contact zone and fault, and always distribute in arc-shape, which is due to the tracking fault system that occurs in the conversion of local tectonic stress field produced in the process of emplacement of magmatic bodies. Just because of this change of local stress field, the ore body shows a location difference. Ore bodies within copper deposit occur in the flanks of compound syncline or the anticline between two secondary synclines, and the minimum principal stress of the regional extrusion stress is in NE−SW direction, which is roughly the same as the minimum principal stress direction of folds in mining area. When the a_{IP} value is between 50° and 60°, the flank of folds is in the largest stress; therefore, it is more likely to form scale space and mineralization. The a_{IP} value is at the unsatisfactory state of 45°, which may be caused by mutual influence, including the complexity of the intrusive body morphology, the non-ideal calculation of angle and the change of the direction of principal stress. The southwest mining section in the Fenghuangshan copper deposits is obviously different. Through analysis, we think that the ore bodies have many features in vertical direction: the upper ore body has inside tendency and is thicker, and the underlying orebody has opposite tendency and is thinner. In horizontal direction, ore body is interrupted, spreading along the NW contact zone, which may be caused by two reasons: the minimum principal stress of regional extrusion stress is consistent with the tensile stress in the shrinkage process of southern part, and the NW track fracture exists in the southern mining area.

Obviously, the relationship between indexes C, C_{Ore} and a_{IP} is nonlinear, so the nonlinear models can be established to simulate them, and we can get two new indexes d_{IP1} and d_{IP2}. We calculate C/d_{IP1} and C_{Ore}/d_{IP2} correlation coefficients and use F-test to analyze the significant relationship between them. The results are given in Table 4.

Table 4 Correlation coefficient and regression effectiveness of mineralization indexes C and C_{Ore} with regional extruding far crustal stress field variables d_{IP1} and d_{IP2}

Regression model	Correlation	$F(1, 2557)$
$C=b_0+b_1d_{IP1}+\varepsilon$	−0.1933	99.9581
$C_{Ore}=b_0+b_1d_{IP2}+\varepsilon$	−0.1834	89.5982

Regression model	$F_{0.05}(1, 2557)$	Regression effect
$C=b_0+b_1d_{IP1}+\varepsilon$	3.8451	Significant
$C_{Ore}=b_0+b_1d_{IP2}+\varepsilon$	3.8451	Significant

From Table 4, significant linear correlations are observed between mineralization indexes C, C_{Ore} and variables d_{IP1} and d_{IP2}, respectively, i.e., d_{IP1} and d_{IP2} have significant contributions to or significant controlling effects on mineralization spatial distribution, and they can be used as ore-controlling indexes to indicate the favorable mineralization degree of geological factors.

4 Conclusions

1) The shape of intrusive body and contact zone has certain effect on the formation and distribution of orebody in skarn deposit, as the complex interface with concavo-convex is more conducive to skarn mineralization than the smooth interface. Taking Xinwuli intrusive body in Fenghuangshan copper deposit as example, on the basis of 3D raster model, we put forward a 3D morphological analysis method to obtain the quantitative relationship between intrusive body morphology and skarn mineralization. The results show that morphological characteristic parameters can effectively indicate the location of concealed ore bodies in skarn deposit.

2) Overlaying 3D raster models of ore-controlling geological factors with orebody raster model, and combining comprehensive analysis, we find the quantitative relationship between intrusive body morphology and skarn mineralization and the most advantageous mineralization positions: (1) In w_{r1G} field model, orebody is mainly located in the parts away from the 1st-trend surface in the range form −25 to 50 m, and skarn mineralization occurs in the rock upper contact zone, where the tangent plane of the rock is approximately consistent with trend surface, and rock contact surface has continuous undulance (in every direction); (2) In w_{r2G} field model, orebody mainly located in the pink area (200±) represents convex and yellow area (20±) represents that rock is approximate consistent with trend surface, and skarn mineralization

occurs in the convex contact zones where the second level (or even higher level) concave and convex zones develop; (3) In a_{IT} field model, orebody is mainly located in the areas with a_{IT} value in the range of 35−70, and skarn mineralization occurs in the parts linking the convex parts and concave parts of contact zone, its convex parts are near the left part and surface undulance degree is small and uniform; (4) In a_{IP} field model, orebody is mainly located in the parts with a_{IP} value in the range of 50−60, some with a_{IP} value in the range of 80−90, and skarn mineralization occurs in the parts where rock contact zone and regional extruding far crustal stress field cross at moderate or high angle. These knowledges can be used to more skarn deposits for future mineral exploration.

3) Magma intrusion and regional extruding far crustal stress field have certain influence on Fenghuangshan copper deposit, and the dilatancy occurs in tectonic system formed in early stage. Due to the differences of the nature of surrounding rock, the heterogeneity of local tectonic stress field, the changes of thermodynamic field and other factors, a series of combined undulating parts with outer convex and inner concave form in rock contact zone. In the subsequent process of rock condensation and release of fluid, the inheritance role of rock contact zone occurs. Because contact zone is a type of dilatancy confluence space, mineral subsides in the parts where physicochemical properties have significant differences between intrusive body and surrounding rock.

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矽卡岩矿床岩体形态定量分析及成矿关系——以安徽铜陵凤凰山铜矿床为例

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摘　要：矽卡岩型矿床矿体的形成和分布主要受岩浆岩的形态及其与围岩的接触带控制。以凤凰山铜矿新屋里岩体为实验对象，运用新方法获得侵入岩岩体形态与矽卡岩矿化的定量关系。首先，基于数学形态学和欧式距离变换，提取岩体三维形态特征参数；然后，分析形态参数和矿体之间的定量关系；最后，进行形态参数和矿化指标之间的相关性分析。结果表明，形态特征参数能有效指示矽卡岩矿床隐伏矿体位置，矿体主要位于：(1)距离一级趋势面−25~50 m的岩体部位；(2)距离二级趋势面200 m附近的外凸部位，附近岩体切平面与趋势面走向一致；(3)岩体原始接触面和趋势接触面之间的夹角为35°~70°的接触带；(4)岩体原始接触面与区域挤压远应力场之间的夹角为50°~60°的岩体部位。这些定量关系可以推广到其他矽卡岩矿床的矿产勘查中。

关键词：岩体形态分析；接触带；数学形态学；矽卡岩矿化；凤凰山铜矿床

(Edited by Bing YANG)