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3D Quantitative Analysis of Xiadian Gold Deposit, Jiaodong Peninsula, China

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Focusing on Xiadian gold deposit in Jiaodong Peninsula, this paper examines the metallogenic information of faults and alteration zone by 3D geological modeling and 3D spatial analysis. Specifically, the geological setting of the gold deposit was reviewed before setting up 3D geomodels on alteration zone field and geologic morphology. Then, the ore-controlling factors were subject to quantitative analysis, including alteration zone field, the fault slope, the fault convexity, the fault concavity, the change from steep to flat and the change from flat to steep. It is concluded that the formation of Xiadian gold deposit involves several ore stages; the gold is more likely to deposit in fault zones of steep-to-flat transformation (4 to 8 rad), with slope between 40° and 50° and undulation between 0m and 20m; the tendency may be attributed to the fluid flow and the physicochemical change of the mineralizing environment. This research highlights the importance of the occurrence exchange of fault zones in future mineral explorations.

1. Introduction

Jiaodong Peninsula is the most important gold producer is China, with a recoverable reserve of over 3,000 tonnes (Goldfarb and Santosh, 2014; Yang et al., 2016a; Figure 1a). On the peninsula, the NNE-trending Zhaoping fault zone hosts several large gold deposits (Yang et al., 2012), namely, Linglong, Dayigezhuang, Xiadian and Xiejiagou gold deposits. Among them, Xiadian gold deposit (recoverable reserve>200 tonnes) is a typical Jiaojia–type gold deposit located in the central part of the fault zone. It is featured by disseminated and/or stockwork ores related to the phyllic alteration (Yang et al., 2016b; Ma et al., 2017). Due to continued mining, Xiadian gold deposit is facing the depletion of reserves. To explore new gold reserve, much research has been done on the geochronology, geochemistry, fluid inclusion, and geodynamic setting in Xiadian area. The existing studies have detailed the ore genesis, and laid the basis for deep mineral exploration, but failed to disclose the 3D orebody distribution or quantify the relationship between gold and ore-controlling factors. Therefore, it is difficult to fully understand the spatial pattern of orebody, or achieve a stable metallogenic prognosis. The development of 3D technologies has greatly furthered our understanding of ore genesis and location, and rationalized the exploration for concealed mineralization. For instance, the 3D quantitative analysis on ore-controlling factors can reveal the metallogenic information of the geological bodies, such as strata, igneous rock, structure, alteration zone, and demonstrate the close spatiotemporal relationship with manganese mineral occurrences. The method links up geological prospecting experience and 3D quantitative prediction. In light of the close association among fault, alteration zone and orebody in Xiadian gold deposit, this paper examines the effect of geological bodies on spatial ore distribution through 3D geological modeling and 3D spatial analysis. Coupled with previous studies, this research realizes the first description of the 3D metallogenic information of the gold deposit, and provides meaningful guidance for mineral exploration.

2. Section headings

Xiadian gold deposit is hosted by Zhaoping fault zone in northwest Jiaodong Peninsula (Figure 1b), the western fringe of the Circum-Pacific metallogenic belt (Figure 1b). The hanging wall of the fault zone is the metamorphic rock of Jiaodong group, and the footwall is Late Jurassic Linglong granite (Figure 1c).

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As a secondary fault of Zhaoping fault, Zhixia-Jiangjiayao fault (length: 8km; width: 150~300m) strikes SE and dips 45° in an undulate manner. In this secondary fault, the hanging wall has three types of secondary structures, respectively trending towards SN, NE and NEE. Located in Zhixia-Jiangjiayao fault and the nearby fractures (Figure 2), the orebodies are largely NE-extending, disseminated ores closely associated with the phyllic alteration. The hydrothermal alteration in Xiadian gold deposit is restricted to Zhixia-Jiangjiayao fault zone (Figure 1c), including phyllic alteration, K-feldspathization, silicification, sulfidation and carbonation. Through multiple alterations, the altered rocks are severely fragmented and concentrated on the contact zone between intrusion and fault zones. These rocks are an impactful indictor for the enrichment of gold.

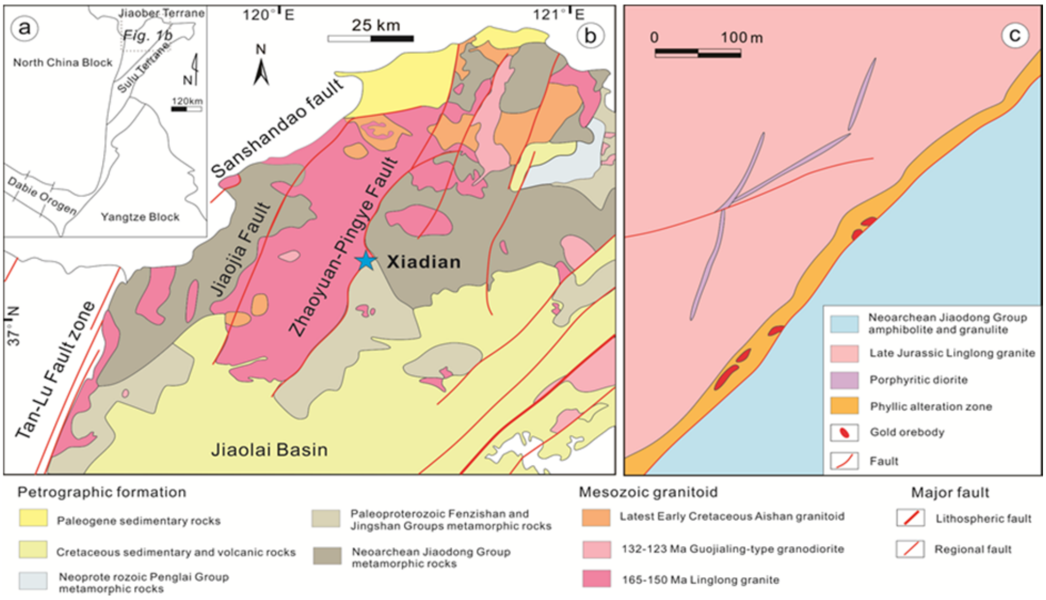

Figure 1: (a) and (b) Simplified geologic map of Jiaodong Peninsula

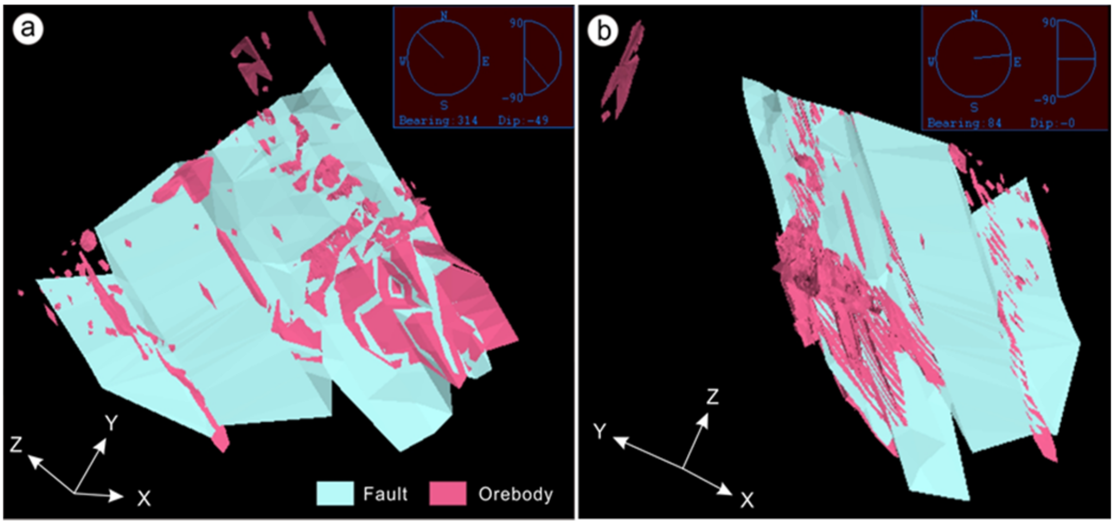

Figure 2: 3D models for the orebodies in Xiadian gold deposit

3. Quantitative Analysis

Please do not use footnotes. For spatial deposit location and distribution, the ore-controlling factors can be described by the distance model in spatial analysis. The metallogenic distance field is often applied to depict the distance or location relationship between a geological body and its surrounding space, i.e. the distance between the point and the field source. Therefore, this paper adopts the 3D raster model to express the units of geological bodies and extract metallogenic information. Besides, the intuitive Euclidean distance field was chosen as the mathematical model of the metallogenic distance field.

3.1 Alteration zone field

Since the disseminated ores are typically in the alteration zone and related to the phyllic alteration, the mineralization field was regarded as a subset of the alteration field. Any gold–bearing unit Mi is influenced by N alteration units in its surroundings, and the intensity of influence is restricted by distance. Hence, the alteration field of gold-bearing unit was described by a distance-weighted field within a certain spherical range. Let there be m alteration zone units. Then, the alteration field of each unit was calculated as follows.

For each mineralized unit that coincides with the altered unit, the field intensity equals the sum of the alteration intensity of this unit and the weighted intensity of the surrounding units; For each of the other units, the field intensity should be derived from alteration intensity by inverse square distance method. The calculation formula is given below:

$$fA = \begin{cases} i_1 + \sum_{j=2}^{m} \frac{i_j}{d_j^2} \Big/ \sum_{j=2}^{m} \frac{1}{d_j^2}; \quad M_1 \in N \\ \sum_{j=1}^{m} \frac{i_j}{d_j^2} \Big/ \sum_{j=1}^{m} \frac{1}{d_j^2}; \ M_1 \notin N \end{cases} \tag{1}$$

where M1 is the coincident unit; i1 is the alteration intensity of the unit; j is the number of units in the buffer zone; m is the total number of units; ij is the alteration intensity of alteration zone unit; N is the set of all units in the buffer zone, dj is the Euclidean distance from the unit to the alteration zone. The distance between geological bodies and units was aligned to the minimum distance: *Distance*=min{D_{PT1}, D_{PT2}, D_{PT3},…, D_{PTn}}.

3.2 Morphological analysis

3.2.1 Slope analysis

The geological interface was represented by the triangulated irregular network (TIN) model. The slope of any point above the model was expressed by the angle between the triangular plane and the horizontal plane, which is equal in magnitude to the normal vector of the triangle and the normal vector of the horizontal plane angle.

The random triangular plane equation of the TIN model and the slope equation are as follows:

$$z = ax + by + c \tag{2}$$

$$slope = \arccos\frac{1}{\sqrt{a^2 + b^2 + 1}} \tag{3}$$

3.2.2 Morphological undulance analysis

The morphological undulance analysis was carried out by the method of Mao et al. The geological variable z(x, y) was decomposed into trend surface and undulance by trending morphology analysis (Equation 4).

$$z(x, y) = T(x, y) + R(x, y) \tag{4}$$

where T(x, y) is a trending surface, i.e. the global change in the reconstructed surface of 3D models; R(x, y) is the remaining surface, i.e. the local change.

The undulance refers to the convexity and concavity of the models:

$$\Delta z = z - \hat{z} \tag{5}$$

where *Dz* is the degree of undulance; Z is the elevation of a point; $\hat{z}$ is the average elevation of the triangle vertices in the TIN model within a fixed range centred on Z.

3.2.3 Morphological transformation analysis

As an ore-controlling factor, the steep-to-flat transformation parts of the fault zone along the dip direction have a significant effect on mineralization, and can be described by geological field. Whereas the mineralization depends on both the distance to the transformation parts and the change intensity, the mathematical model of the steep-to-flat transformation field consists of two factors: distance d and intensity i

Considering the combined effect of steep-to-flat transformation fields, the intensity was weighted by the inverse distance square method. Then, a mathematical model was constructed by d and i:

$$f=\sum_{j=1}^{m}\frac{i_j}{d_j^{\ 2}}\Bigg/\sum_{j=1}^{m}\frac{1}{d_j^{\ 2}} \tag{6}$$

where ij is the intensity of steep-to-flat transformation parts; *dj* is the Euclidean distance of the unit to steep-to-flat transformation parts.

The morphological transformation analysis hinges on the extraction of the transformation points in the fault zone and the calculation of dips. The two operations are carried out as follows (Figure 3).

Step 1: Starting with the side of the exploration line, take 1/3 of the exploration line spacing as the advancing distance, and generate several vertical planes along the exploration line that intersect the TIN model of the fault zones. Then, extract all of the intersection points and calculate their dips.

Step 2: For each transformation point on sections, define the change of dip as the radian difference of dips between the next point (in the deep direction) and itself. Regard the change from flat to steep as positive (iP> 0), and the opposite change as negative (iV< 0).

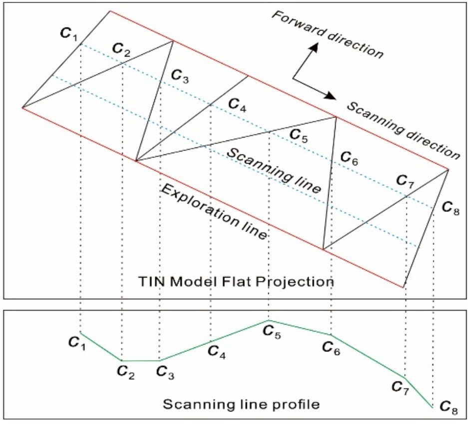

Figure 3: Extraction of transformation points

After the extraction of all transformation points and calculation of intensity, the field of steep-to-flat part fP or fV can be calculated by Equation 7 below.

$$f\mathrm{P}=\sum_{j=1}^{m}\frac{i\mathrm{P}_j}{d\mathrm{P}_j^{\ 2}}\Bigg/\sum_{j=1}^{m}\frac{1}{d\mathrm{P}_j^{\ 2}} \tag{7}$$

where iPj is the transformation intensity; dPj is the Euclidean distance between units to points.

4. Results and Discussion

Based on the 3D geomodels of Xiadian gold deposit, the following parameters were extracted: the alteration zone field (fA), the fault slope (gA), the fault convexity (waF), the fault concavity (wbF), the change from steep to flat (fP) and the change from flat to steep (fV) (Figure 4).

The scatter diagram of fA vs. Au (Figure 6) shows a certain relationship between the average gold content in one unit (Au) and fA. The main ore enrichment space was located between 0 and 120 of fA. In general, the alteration field intensity is positively correlated with gold grade. Three mineralization peaks appeared in (30, 120), (60, 120) and (70, 120). This means the formation of Xiadian gold deposit involves several ore stages, which is also demonstrated by the geological features and geochronology

As shown in Figure 5, there is also a certain relationship between Au and gF. Specifically, the fault zone slope ranged from 10° to 80° near the main ore enrichment space, peaking between 40°C and 50°C. Moreover, the slopes of the fault zones changed in the same direction with the variation in the value of Au, showing a symmetrical distribution (Figure 6).When the slope was greater than 80°, the gold grade was extremely low, indicating the absence or weak presence of enrichment space. The regular pattern reveals that the ore-forming process of Xiadian gold deposit is strictly controlled by Zhaoping fault. The gradient of fault surfaces may reflect the physicochemical change of the mineralizing environment, an influencing factor of gold migration and deposition. According to the scatter diagram of waF-Au (Figure7), high Au values mainly occur in the units with waF ranging from -140m to 50m. The peak of Au appeared in the relatively flat range of the undulation of the local fault zone, with waF varying between -20m and 0m. The Au decreased with the increase of concave/convex degree, and the degree of gold enrichment in the concave parts surpassed that in the convex parts. The Au value was relatively low in the units, whose waF values are smaller than -140m or greater than 50m, a signal of the absence or weak presence of enrichment space.

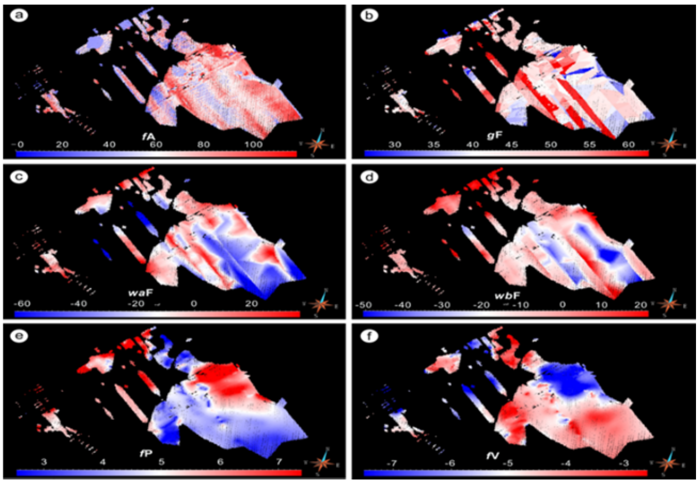

Figure 4: Quantitative analysis results for the ore-controlling factors of the Xiadian gold deposit. (a) fA; (b) gF; (c) waF; (d) wbF; (e) fP; (f) fV.

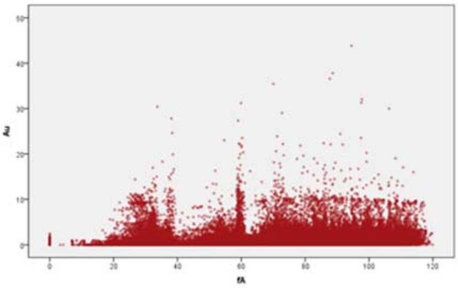

Figure 5: Scatter diagram of fA vs. Au

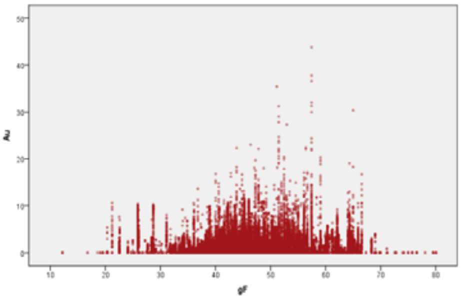

Figure 6: Scatter diagram of gF vs. Au

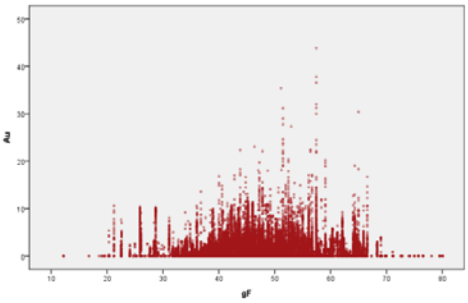

Figure 7: Scatter diagram of waF vs. Au

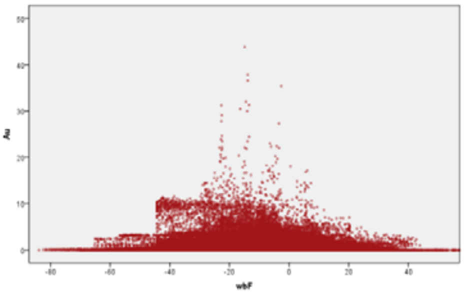

Figure 8: Scatter diagram of wbF vs. Au

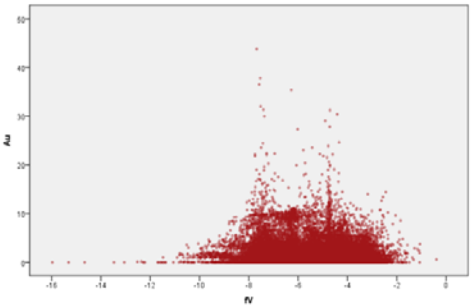

Figure 9: Scatter diagram of fV vs. Au

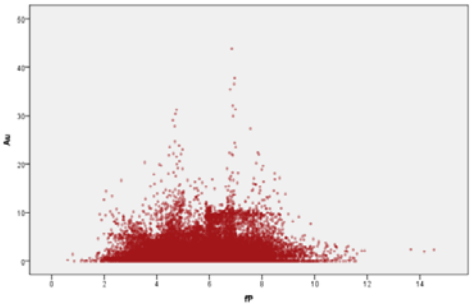

Figure 10: Scatter diagram of fP vs. Au

The scatter diagram of wbF-Au (Figure 8) reveals that the Au value was much higher in the units whose wbF value fell between -100m and 50m than in the other units. The interval of Au peak also occurred at about -20m to 0m, which represents relatively flat fault zones. With the increase in the concave/convex degree of fault zone, the gold grade in orebodies exhibited an increasing trend. These phenomena indicate that the morphology of fault zone, especially the low-degree concave and convex, controls the occurrence and distribution of orebodies. The influence may be attributed to the hydrothermal fluid flow and convergence.

The scatter diagrams of fV-Au (Figure 9) and of fP-Au (Figure 10) both demonstrate the strong association between gold and fault transformation. The most of orebodies occurred in the area with fP value at 0~12 or fV value at 0~12 rad. The peak ranges of Au were observed in 4~8 of fP or -8~4 of fv. All units exhibited an overall symmetrical distribution for the ore-controlling factor. The gold ore was not enriched when the fP value was greater than 12 or smaller than 2. Thus, it is concluded that the main gold enrichment space usually exists in the main fault zone of steep to flat transformation. It is possible that the steep to flat transformation of fault zones are the abnormal locations of hydrothermal fluid migration. Based on field features, these parts should develop along the horizontal direction of fault zones. Thus, the speed and flux of hydrothermal fluids are bound to change in this environment, leading to the gold precipitation

5. Conclusion

This paper presents a detailed 3D quantitative analysis on the alteration and fault zone of Xiadian gold deposit in Jiaodong Peninsula. The main conclusions are as follows: the gold-bearing units were influenced by the alteration, indicating that the main ore enrichment space is located between 0 and 120 of the alteration field. The analysis on alteration zone field shows that the formation of Xiadian gold deposit involves several ore stages. The fault is the most important ore-controlling factor. Besides, the gold is more likely to deposit in fault zones of steep-to-flat transformation (4 to 8 rad), with slope between 40° and 50° and undulation between 0m and 20m. The tendency may be attributed to the fluid flow and the physicochemical change of the mineralizing environment. In light of our research, the occurrence exchange of fault zones should be further explored in mineral exploration.

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