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The geochemical multi-fractal characteristics and mineralization of the Dehelongwa copper-gold deposit

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Abstract The spatial distribution of ore-forming elements is the result of interaction and influence among multiple factors in the process of mineralization, and is the specific embodiment of non-linearity and coupling of mineralization. The fractal theory has such functions as to characterize non-lineariry and coupling, and can find out the deterministic law from the complicated coupling process. The primary geochemical fractal distribution of metallogenic elements such as Cu and Au possesses the characteristics of multi-fractal distribution in the Dehelongwa copper-gold deposit. Copper follows 2-d fractal distribution, and Au follows 3- or 4-d fractal distribution. The primary geochemical fractal distribution has a certain similarity on the same prospecting line, and this similarity is not obvious among different prospecting lines. The secondary geochemical fractal distribution of Cu and Au is higher in similarity, and simpler than the primary geochemical fractal distribution. These results show that the mineralization of Cu and Au is out of sync and also is inconsistent in this deposit, and the mineralization of Cu mainly experienced two mineralization stages, while the mineralization of Au experienced three to four mineralization stages. Besides the mineralization of Cu and Au shows a certain direction and along the strike of vertical orebodies it is relatively balanced. While along the strike of the ore bodies the mineralization of Cu and Au shows a significant difference. The hypergenic geologic process has a certain effect on the balance of spatial distribution of Cu and Au . From these it can be seen that the mineralization process of this deposit is well characterized by the geochemical fractal distribution of Cu and Au.

Key words geochemistry; multi-fractal; mineralization; Dehelongwa

1 Introduction

The contents of ore-foming elements in endogenous deposits show a wide range of spatial variations and are distributed very unevenly. This kind of variation trend also shows some certainty, though in a paradoxical case. This certainty is partly hidden and partly visible, thus arousing great interest in the study of the spatial distribution of geochemical elements. Supported by analytical results for a large number of samples this method has achieved good results in finding deterministic connections of spatial distribution of elements. However, because most of these statistical distribution methods are based on the statistical law of large numbers, and the spatial distribution and spatial scale of geochemical samples are not taken into account, they generally have a good effect in measuring general values of the ore-forming elements, but cannot describe the outlier values (Cheng, et al., 1996, 1997, 1999a, b; Cheng, 2000).

The fractal theory is a very active subfield of the nonlinear field, which is very consistent with the nonlinearity and self-similarity of objective things in nature. Spatial distribution of ore-forming elements is the result of mineralization, and the mineralization is affected by the combined effects of a variety of geological facto, which is a nonlinear and coupling process. Thus, the spatial distribution of ore-forming elements is also characterized as being nonlinear. A large number of researches show that besides the spatial distribution of ore-forming elements (Mao et al., 2004), the distribution of the deposit (Carlson, 1997; Li et al., 1996), faults in the mining district (Cello, 1997; Mao et al., 2004), ore grade (Jin, 1998; Xie et al., 2004), ore body thickness (Thomas et al., 2001; Xie et al., 2002), hydrothermal fluids (Gharbir et al., 2001), etc. are all characterized by fractal distribution. However, studies on the relationship between fractal forming elements, geochemical distribution and mineralization are still at the initial stage.

Research on the Dehelongwa copper-gold deposit is relatively immature, the current study puts its focus on petrochemistry, tectonic settings at the time when magmatic rock bodies were forming, metallogenic rules and fluid inclusion characteristics. Studies suggest that the volcanic rocks in this area are similar to ocean island basalts (Fan et al., 2007); the tectonic environment at the time when the rocks were forming has such a feature as evolving from tensile transition to closed island-arc type (Kou et al., 2007); fluid inclusions were resultant from the ore fluids of mid-high temperature, low salinity, medium density and medium pressure (Fu et al., 2009, 2011; Cao et al., 2011); the ore-forming materials were sourced from the mixed crust-mantle. In this paper the fractal theory (Fu et al., 2010) was used to analyze, in detail, the primary and secondary geochemical characteristics of fractal distribution of ore-forming elements such as Cu and Au, in order to reveal the relationship between the spatial distribution of ore-forming elements and mineralization, and to explore the metallogenic mechanism of this deposit.

2 Geology

The Dehelongwa is a newly discovered copper-gold magmatic hydrothermal deposit, which is dominated by copper and associated with gold. The deposit is located in the eastern part of Tongren Country, Huannan Prefecture, Qinghai Province. Geotectonically, it is located in combined part of Southern Qilian-Western Qinling, which also lies at the juncture of the Qinling-Qilian-Kunlun Mountains and belongs to the West Qinling metallogenic zone (Cao et al., 2011, 2012; Fu et al., 2010) (Fig. 1). In recent years, extensive achievements have been made in this mining area and most researchers believe that this area is a compound orogenic belt with a complicated history of oceanic crust evolution (Fu et al., 2010; Cao et al., 2012; Xiao et al., 2009; Zhang et al., 2007).

The deposit stratigraphy is relatively simple, which is mainly composed of the Shangyan Formation of the Lower Permian Daguanshan Group and the Xiayan Formation of the Lower Triassic Longwuhe Group. The Shangyan Formation of the Lower Permian Daguanshan Group consists mainly of slightly metamorphic medium-fine-grained feldspar quartz sandstone, argillite and silicified marble; the Xiayan Formation of the Lower Triassic Longwuhe Group is made up of a set of slightly metamorphic siliceous rocks, which shows a significant rhythm change and clear features of turbidite, among which there is a fault-contact relationship (Fu et al., 2010; Cao et al., 2012; Xiao et al., 2009; Zhang et al., 2007).

The mining area is situated on the southern limb of the Goncharov duplex anticline. As this area has experienced a number of tectonic movements, fold and fault structures are well developed. In the Goncharov duplex anticline is developed a series of fold structures. The fault structures were formed in the Late Variscan-Indosinian period. The overall tectonic line is in the NW-SE direction, superimposed by NE-trending faults, which are the main ore- and rock-controlling structures in this area (Fu et al., 2010; Cao et al., 2012; Xiao et al., 2009; Zhang et al., 2007) (Fig. 1).

Strong magmatic activity had taken place in the mining district and the magmatic rocks are Indosinian I-type granites which were formed in the orogenic belt. The main body of the Goncharov pluton is composed of diorite granodiorite (Cao et al., 2011, 2012; Fu et al., 2010; Xiao et al., 2009). The occurrence of the pluton is obviously controlled by faults (Fig. 1).

Orebodies are located mainly in the contact zone of rock bodies, the fractured alteration zone of Lower Triassic clastic rocks and joint intensive belt. The oerbodies are parallel in lateral, end-to-end alignment in strike, and obviously controlled by structures (Fig. 2). In the ore, metalliferous minerals are mainly chalcopyrite, pyrite, magnetic pyrite, arsenopyrite, natural gold, molybdenite, etc., and gangue minerals are quartz, calcite, sericite, hornblende, plagioclase, etc. The ores mainly exhibit emulsion texture, radial pattern texture, poikilitic texture, metasomatic texture and banded-massive, disseminated, veinlet disseminated, veined, mesh-veined, granophyric, brecciated and crumpled structures. The mineralization process is relatively simple. It can be divided mainly into magmatic hydrothermal metallogenic epoch and superficial metallogenic epoch; in the superficial metallogenic epoch some simple oxide minerals were formed; in the magmatic hydrothermal metallogenic epoch the primary ores were formed in this deposit. There were involved two mineralization stages: the quartz-pyrite mineralization stage and the arsenopyrite mineralization stage (Cao et al., 2011).

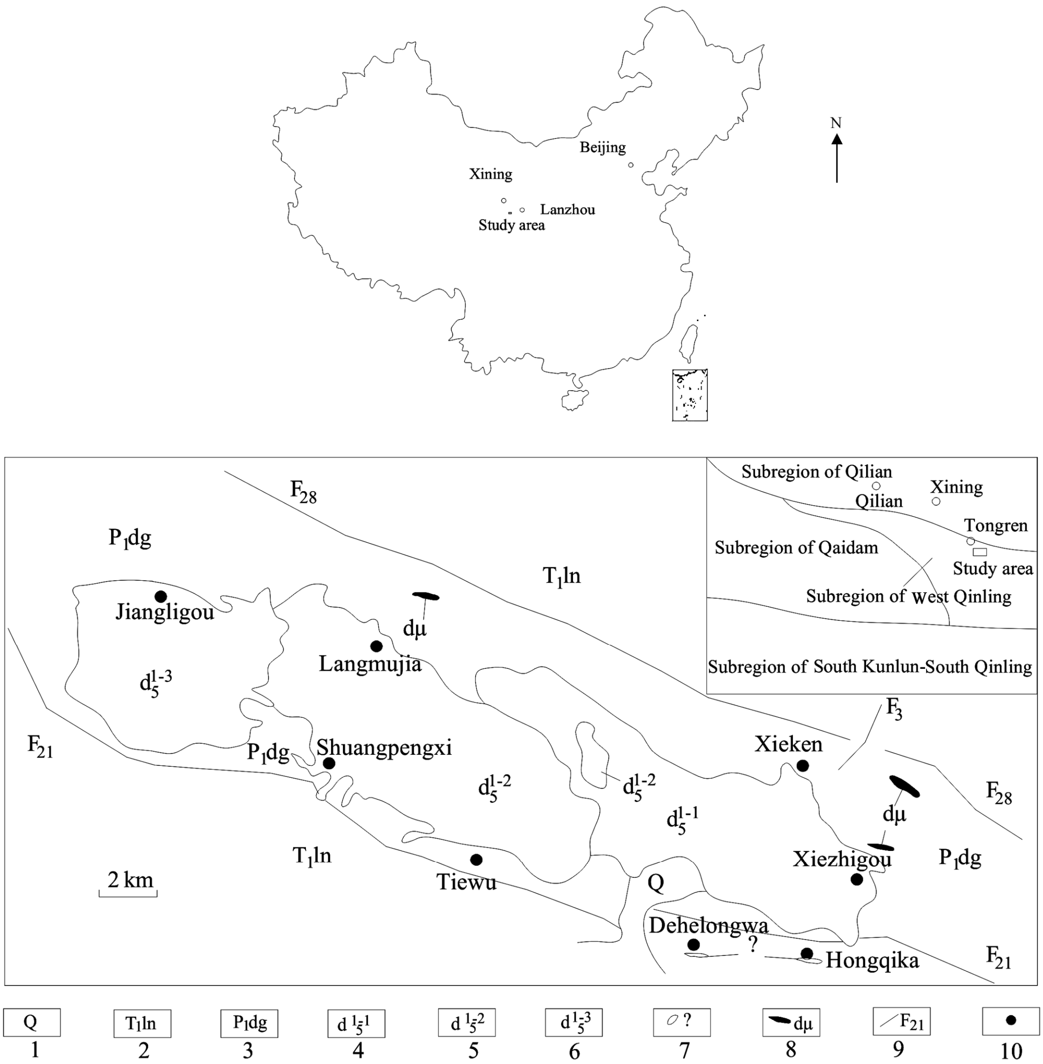

Fig. 1. Regionally geological map of the Dehelongwa deposit (modified from Zhang Tao, 2007). 1. Quaternary; 2. Triassic Lower Longwuhe Group; 3. Lower Permian Daguanshan Group; 4. diorite; 5. granodiorite; 6. porphyritic granodiorite; 7. lamprophyre dyke; 8. diorite dyke; 9. fault; and 10. copper-gold deposit.

3 The geochemical multi-fractal characteristics of Cu and Au

Mineralization is a geological anomalous event occurring within the Earth's interior. Especially the formation of endogenous deposits usually underwent a long metallogenic process. During that process, the formation of the ore-forming elements was effected by a combination of many factors, and it is also an integrated product of multi-episodic and integrated processes. Enrichment and dispersion effects of ore-forming elements are the comprehensive reflection of interactions among various factors affecting mineralization and the mineralization would affect the formation of ores many times. In the mineralization process, the exchange between ore-forming material and energy inside the geological body is a very complex dynamic process, which is irreversible. It is difficult to simulate and reproduce these scenes by other ways, and this kind of nonlinearity and coupling of mineralization has been commonly accepted as a bizarre process (Cheng, 2007; Shen, 2010).

The spatial distribution of ore-forming elements is a concrete manifestation of nonlinear and coupling processes of mineralization, which is also the historical record of the hybrid mineralization mechanism. Therefore, some changes have taken place in research on the spatial distribution of elements. Traditional studies on the spatial distribution of elements put their focuses on identifying the abnormal areas of ore-forming elements, and via the distribution of primary halos. Primary superimposed halos and secondary dispersion halos to forecast concealed orebodies. In recent years, the spatial distribution characteristics of elements with respect to their singularity, non-linearity and coupling have attracted more and more attention. The fractal theory, as an important branch of nonlinear sciences, is very active in research on the spatial distribution of the metallogenic elements. As such, great achievements have been made in this area, and most of the results put thier focuses on the division of space outliers, the distribution structure of ore deposits (points) and metallogenic prediction.

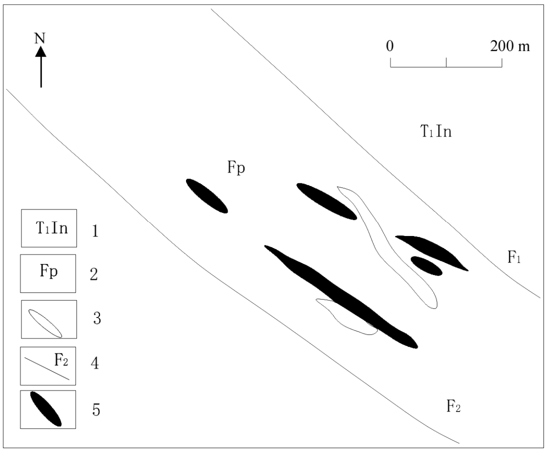

Fig. 2. Sketch geological map of the Dehelongwa Au-Cu deposit (Zhang, 2007). 1. The Lower Triassic Longwuhe Formation; 2. broken alteration belt; 3. lamprophyre dyke; 4. fault; 5. copper-gold ore body.

In this study, the contents of Cu and Au in the samples taken from the Dehelongwa copper-gold deposit, including 529 rock samples from six boreholes and 1048 soil samples from the surface, were analyzed by fractal statistics. As seen from the results, relatively large differences are noticed in the contents of Cu and Au either for the surface soil samples or for the borehole rock samples and no rules of variation were found. This is also a reflection of mineralization singularity.

Numerous studies have indicated that the distribution of ore grades follows the lognormal distribution which is also known as power-law distribution (Xie et al., 2002; Cheng, 2007). But relatively little fractal study has been conducted on the content distribution of orebodies and their peripheries. From the mechanisms of enrichment and dispersion of ore-forming elements and the process of mineralization, it can be seen that the enrichment mechanism of ore-forming elements is of no difference, either in orebodies or in their peripheries of the same deposit, that is to say, both of them are the product of the same mineralization. Therefore, the spatial distribution regularities of primary halos of ore-forming elements should also obey the power-law distribution, so, r, which represents the scale (element content), and $N(r)$, which is the cumulative number of samples whose element contents are greater than or equal to r, have the following power-law distribution relationship:

$$N(r)=r^{-D}$$

The satisfaction of this relationship is also called the obediance fractal distribution. D is the factal dimension. It can be worked out from the least square regression by taking logarithms from both sides:

$$\log N(r)=\log K-D\log r$$

where r is the content of ore-forming element, $N(r)$ is the cumulative number of the samples whose ore-forming element content is greater than or equal to r, and K is a constant.

3.1 The primary geochemical fractal characteristics of Cu and Au

Shown in Fig. 3 is the fractal distribution diagram of Cu and Au in boreholes, which are ZK01-1, ZK15-1, ZK16-1, ZK24-1, ZK24-2, ZK24-3, in the Dehelongwa copper-gold mining district. It is seen from the figure that their fractal distribution has the following characteristics:

(1) As can be seen from all the six boreholes, the fractal distribution of Au is more complicated than that of Cu, indicating that the mineralization process and enrichment mechanism of Au are complicated than those of Cu; there may have been more mineralization episodes involved in the enrichment of Au. Meanwhile, it may also explain why the mineralization of Cu has little correlation with that of Au.

(2) The fractal distribution of the same element among the six boreholes has some similarity, but of a low degree, indicating that the mineralization of Cu and Au is uneven in this mining district, i.e., different locations have different mineralization intensities.

(3) The fractal distribution of Cu among the six boreholes can be basically fitted well with two, but with three in a few cases, straight lines, indicating that Cu mineralization in this mining district mostly involves two main stages, but three stages in a few cases.

(4) The fractal distribution of Cu and Au in the three boreholes on the 24th exploration line, which are ZK24-1, ZK24-2, and ZK24-3, has some similarities. By taking the location of these three boreholes into account, which are not far from each other and on the same exploration line, it is indicated that mineralization in this area has a certain balance within a small range and along one exploration direction. Moreover,

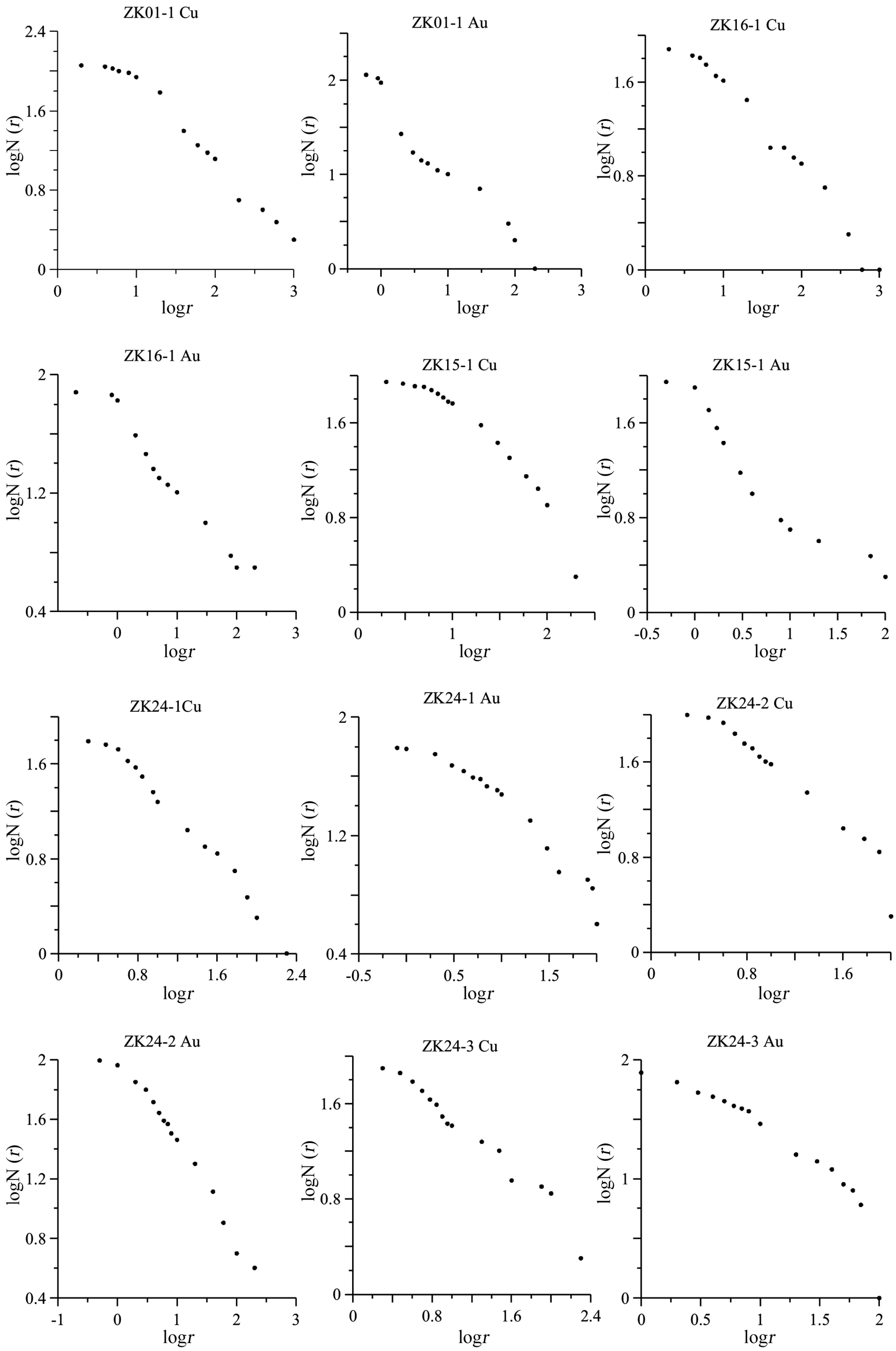

Fig. 3. The primary geochemical fractal distribution of the elements Cu and Au in the Dehelongwa copper-gold deposit.

the fractal distribution diagram of Cu and Au among those three boreholes also has a certain similarity, indicating that the mineralization of Cu and Au in this section has some correlation, and there may be a certain degree of synchronization.

(5) The fractal distribution of Au in the three boreholes on the 24^{th} exploration line is greatly different from that for the other three boreholes. The diagram of fractal distribution on the 24^{th} line is relatively simple. If piecewise fitting is taken, perfect fine fitting will be realized by taking two straight lines. This probably explains why Au mineralization on the 24^{th} exploration line is relatively simple and mineralization stages are relatively less. Gold enrichment may have involved two stages.

(6) The fractal distribution of Au in boreholes ZK01-1, ZK15-1 and ZK16-1 shows obvious four-dimensional characteristics, indicating that Au mineralization in these regions underwent at least four stages of enrichment. Meanwhile, on the fractal distribution diagram, the distribution trend of sample points from the top to the bottom involved four stages, i.e., steep-gentle-steep-gentle, indicating that Au mineralization also experienced four stages, i.e., uneven enrichment-more uniform enrichment-uneven enrichment-more uniform enrichment.

(7) A common characteristic feature of fractal distribution of Cu and Au in these six boreholes is that the fitting straight line of the fractal distribution of Cu and Au is steeper in the high-content segment and its fractal dimension is larger, indicating that the samples taken from the high-content segment are only different slightly, where mineralization is better balanced and relatively stable.

(8) The diagram of fractal distribution trend of Cu in these six boreholes shows such a trend as to be moderate in the upper part but lower in the steep part, indicating that differences among low Cu-content samples taken from the region are relatively large, and the mineralization is uneven; differences among high Cu-content samples are small and the mineralization is relatively uniform.

3.2 The secondary geochemical fractal characteristics of Cu and Au

Shown in Fig. 4 is the fractal distribution diagram of Cu and Au in surface soil samples. It can be seen from this figure that the secondary geochemical fractal distribution of Cu and Au has the following characteristics:

(1) With respect to the primary geochemical fractal distribution of Cu and Au, the similarity of their secondary geochemical fractal distribution has increased, and generally they all have a characteristic feature of two-dimensional fractal distribution, which may indicate that the supergene geological process has effects on the equalization of distribution of the elements Cu and Au distribution. In the supergene geological process, the spatial differences between Cu and Au tend to decrease.

(2) The low-content segment of Cu has a flatter fractal distribution pattern, while it shows a similar fractal distribution pattern with primary samples from the high-content segment of Cu, indicating differences tend to decrease for the samples from the low-content segment, the supergene geological process has a more obvious effect on equalization in the low-content segment.

(3) There are larger differences between the secondary and primary geochemical fractal distributions of Au. The secondary geochemical fractal distribution can be fitted well with two straight lines, which shows that supergenic geological processes have great effects on the equalization of spatial distribution of Au, and differences among the samples have been greatly reduced. The low-content segment is relatively flat. This feature is identical to the secondary geochemical fractal distribution characteristics of Cu.

(4) From the characteristics of element content variation, it can be seen that the low-content segment of Cu shows a trend of further enrichment, which is not obvious in the high-content segment, but the variation trend of Au is balanced overall. This may be related with the differences in supergene geological activity of Cu and Au.

4 Discussion

The formation of ore deposits is a complex geological process that is mostly caused by coupling effects of multi-geological process and multi-stage mineralization. Particularly for the endogenous deposits, in the process mentioned above the formation, migration, precipitation and aggregation of ore-bearing fluids were all affected by a series of factors such as tectonic movement, fluid pressure, fluid properties, changes of geochemical environment of fluid flow, and exchange of material and energy between fluids and rocks. Between the formation of orebodies and those affecting factors there is a very complex nonlinear relationship. It is this complex nonlinear mechanism that controls the migration, dispersion, enrichment and other geochemical behaviors of the ore-forming elements. Nonlinear coupling among these factors seems very complicated, but the formation and localization of a deposit have its deterministic attributes, i.e., this complex coupled chaotic system of mineralization is not entirely chaotic, there is always a deterministic evolution trend and a certain outcome.

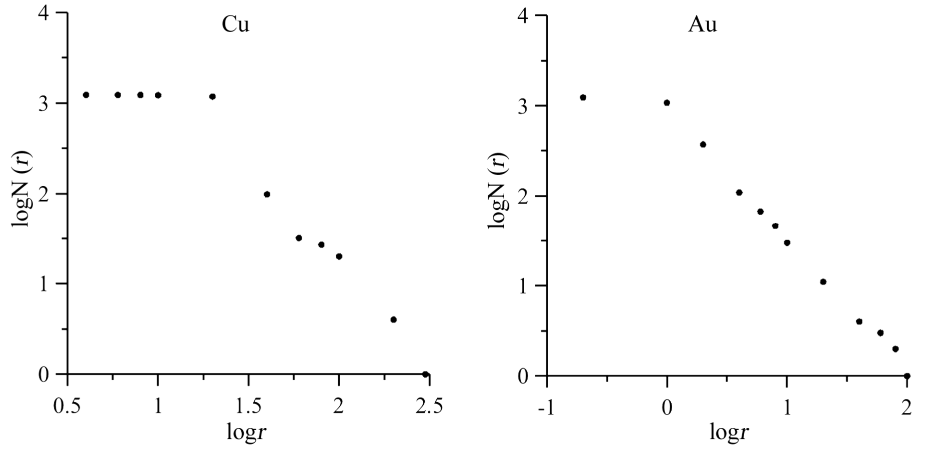

Fig. 4. The secondary geochemical fractal distribution of Cu and Au in the Dehelongwa copper-gold deposit.

Since mineralization is a long complex geological process, and is also irreversible and non-repeatable, it is kaleidoscopic, colorful, but also has brought about some difficulties to the study of mineralization. The spatial distribution of ore-forming elements is the result of the chaotic system with a complex coupling and deterministic trend, and it is also the embody of interactions among various factors in the mineralization process, which bears a variety of interact information. Thus, research on the spatial distribution of ore-forming elements can reveal the mechanism of mineralization.

Multi-time and multi-stage characteristics of the mineralization process are the root causes that make ore-forming elements disobey the normal distribution, so by using traditional statistical methods one can not characterize the inherent distribution well, because the spatial distribution of ore-forming elements and the relationship among factors affecting this spatial distribution is nonlinear. The fractal theory has the function to score such nonlinear spatial distribution, which can score certainty regularities from the nonlinear spatial distribution of ore-forming elements.

According to Cao Yonghua (2011), the formation of the Dehelongwa copper-gold deposit mainly experienced two metallogenic epochs, i.e., the magmatic hydrothermal metallogenic epoch and the superficial metallogenic epoch, during the superficial metallogenic epoch, malachite, azurite and other oxide minerals were mainly generated. The magmatic hydrothermal metallogenic epoch can be divided into two stages. The first one is the quartz-pyrite stage, with a mineral assemblage of quartz, calcite, chalcopyrite, pyrite, galena, sphalerite, arsenopyrite, etc.; the other is the arsenopyrite stage, with a mineral assemblage of quartz, calcite, actinolite, arsenopyrite, etc. As can been seen from the division of metallogenic stages, Cu mineralization in this area occurred mainly at the first stage, and Cu mineralization at the second stage is relatively weak, while the precipitation of gold is common in these two stages, with no significant difference.

In combination with the fractal distribution characteristics of Cu and Au in six boreholes and surface soil, the distribution of ore-forming elements in the boreholes in this area represents the primary spatial distribution of the ore-forming elements Cu and Au, which is the product of magmatic hydrothermal metallogenesis. The fractal distribution of Au in the six boreholes is generally more complex than that of Cu, which is consistent with the actual situation that the mineralization mechanism of Au in this area is more complex than that of Cu. The fractal distribution of Cu can be fitted with two piecewise lines, indicating that there are two main mineralization epoches or stages for Cu, which is consistent with the situation of this region. The fractal distribution of Cu and Au has little similarity, which is also the same as the situation that the mineralization of Cu and Au has little consistency. The fractal distribution of Au shows a multi-stage characteristic feature, and partly has a slow-steep-slow-steep regularity, indicating that the mineralization of Au can be further divided into four sub-stages on the basis of two-stage magmatic hydrothermal metallogenic mechanism. There may be an intermittent period for each sub-stage mineralization. Three out of the six boreholes were drilled on the same exploration line. There are similarities for the fractal distribution of Cu and Au on the same exploration line, but the fractal distribution characteristics on different exploration lines vary greatly, which may illustrate a certain balance of mineralization along the strike of vertical ore bodies and large differences in mineralization toward the orebody direction.

The fractal distribution characteristics of Cu and Au in surface soil are those of the secondary geochemistry fractal distribution of Cu and Au. It can be seen from the surface fractal distribution characteristics of Cu and Au that secondary mineralization has a trend to balance the distribution of Cu and Au in this area, which is basically the same as the case of secondary geological processes.

5 Conclusions

Based on the above analysis and discussion of the fractal distribution of primary and secondary metallogenic element contents of the Dehelongwa copper-gold deposit, the following initial understanding can be achieved:

(1) The primary and secondary geochemical distribution of Cu and Au in the Dehelongwa copper-gold deposit has some fractal characteristics, and the secondary geochemical fractal distribution of Cu and Au has the characteristics of two-dimensional fractal distribution, the primary geochemical fractal distribution of Cu is two-dimensional in most cases, but three-dimensional in a few cases; the primary geochemical fractal distribution of Au is more complicated: three-dimensional in some cases and four-dimensional in some other cases.

(2) The different primary geochemical fractal distribution characteristics of Cu and Au indicate the inconsistencies of Cu and Au mineralization in this deposit. As viewed from the fractal distribution characteristics, Cu mineralization mainly underwent two stages, and Au mineralization experienced three to four stages, which is consistent with the research results of magmatic hydrothermal mineralization in this mining district, indicating that the primary geochemical fractal distribution of Cu and Au can well depict the mineralization process in this area.

(3) On the same exploration line there are some similarities for the primary geochemical fractal distribution of Cu and Au, but the primary geochemical fractal distribution characteristics on different exploration lines are greatly variable, indicating that along the perpendicular direction of orebodies the mineralization is more even, along the strike direction of orebodies there are significant differences; different spatial locations have different mineralization intensities.

(4) The secondary geochemical fractal distribution of Cu and Au has a high-degree similarity, it is much simple as compared to the primary geochemical fractal distribution. This may indicate the supergene geological process has some balancing effect on the spatial distribution of Cu and Au.

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