Characterization of multi-type mineralizations in the Wandongshan gold poly-metallic deposit, Yunnan (China), by fractal analysis

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ABSTRACT

The Wandongshan gold poly-metallic deposit, one of the largest gold deposits in China, is composed of magmatic Fe-Au (M-FA), porphyry Cu-Au (P-CA), skarn-type poly-metallic (S-P) and laterite-type Fe-Au (L-FA) orebodies, manifesting complex multi-stage mineralizations. The vertical distributions of concentrations of ore-forming elements (Au, Ag, Cu, Pb and Zn) in 101 mineralized drillcores with various mineralization types are examined using self-affine fractal and multifractal models. The study reveals that the vertical distributions of element concentrations are controlled by ore type, geological position and spatial co-existence of multi-type mineralizations. Generally, element distributions in most drillcores dominated by M-FA orebodies exhibit higher Hurst exponent ($H$) and lower correlation dimension ($D_2$) than those dominated by P-CA or S-P orebodies, representing that the M-FA mineralization has a strong persistent element distribution and weak compact distribution of high element concentrations. This is likely due to the wide transportation of ore-bearing fluids and heterogeneous metal enrichment during formation of M-FA orebodies. Variations in mathematical parameters for M-FA dominated drillcores are strongly influenced by variations in geological positions and corresponding orebody shapes. High element concentrations are more compact mostly in contact areas than in distal Triassic carbonates. The spatial co-existence of multi-type mineralizations causes strong persistence of element distributions and weak compactness of high element concentrations. The correlations of $D_2$ for Au vs. Cu and Pb vs. Zn in M-FA dominated and L-FA drillcores are high, suggesting that Au and Cu have similar distribution patterns, and Pb and Zn have similar distributions. In P-CA and S-P orebodies, only Pb and Zn exhibit similar spatial distributions.

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1. Introduction

Quantitative descriptions of the distributions of ore-forming elements in mineral deposits are important to the understanding of ore-forming processes. The concentrations of elements in mineralized zones often exhibit heterogeneous and skewed distributions, which commonly display similarities across several magnitudes and can be described by various fractal models (Deng et al., 2009, 2010a; Cumié et al., 2010; Jiang, et al., 2012; Monecke et al., 2001; Wan et al., 2010; Wang et al., 2011a). The fractal models include box-counting model (Deng et al., 2001, 2006; Mandelbrot, 1983), number-size model (Turcotte, 2002; Wang et al., 2010a,b), concentration-area model, perimeter-area model (Cheng, 1995), self-affine model (Wang et al., 2007) and multifractal model (Agterberg et al., 1996; Arias et al., 2011; Cheng, 1999; Deng et al., 2008, 2011; Wang et al., 2011b). Some fractal indices in these models, such as the Hurst exponent ($H$) in the self-affine model and the multifractal spectrum in the multifractal model, have been effectively applied in various disciplines to characterize different properties of a system based on a geochemical dataset. The Hurst exponent was proposed by Hurst (1951) and has been widely used in geosciences (Turcotte, 1997). A larger $H$ means a stronger persistence and less erratic distribution. Wang et al. (2011a) and Zuo et al. (2009) found that, based on $H$, element distributions in skarn, porphyry and structure-controlled disseminated deposits show persistent behavior, indicating stably repetitions (or recurrences) of mineralization.

The multifractal technique was first introduced by Mandelbrot (1974) and applied in the study of energy dissipation in turbulence. Since then, it has been applied to a large number of empirical and theoretical studies of a wide variety of subjects, such as fractures (Agterberg et al., 1996; Arias et al., 2011) and geochemical data (Wang et al., 2007), in geology. Deng et al. (2011) and Wang et al. (2011b) found that, based on multifractal analysis, the compactness of element distributions in skarn and structure-controlled disseminated-veinlet deposits is different in various mineralization segments.

The Wandongshan gold poly-metallic deposit, one of the largest gold deposits in the Sanjiang ore belt in SW China (Deng et al., 2010b), is characterized by a complex geological background and multi-stage
Fig. 1. Geological sketch map of the Wandongshan gold poly-metallic deposit, Beiya, Yunnan, China. (The original data comes from the Yunnan Geology and Mineral Resources Co. Ltd., 2006).

Fig. 2. Photos of typical orebodies in the Wandongshan poly-metallic deposit, Beiya, Yunnan, China.
mineralizations. Although the geological characteristics of the deposit have been researched by Xu et al. (2006, 2007a,b), the spatial distributions of various ore-forming elements have not been previously described. The multi-type mineralizations provide an opportunity to study the various ore-forming processes using a mathematical approach, as is carried out in this paper.

2. Geological setting

The Wandongshan gold poly-metallic deposit, in the Beiya orefield, is located about 90 km north of Dali city, in western Yunnan, China, and is geologically situated to the east of the Jinshajiang suture that bounds the western part of the Yangtze Plate (Xu et al., 2007a). The Beiya orefield with an area of about 30 km² is located nearby the core of an N–S trending syncline. Only small–size faults are locally developed in the orefield (Xu et al., 2007b). The Beiya orefield contains a reserve of more than 150 t of Au, 1500 t of Ag, 0.2 Mt of Cu, 40 Mt of Fe and 0.5 Mt of Pb and Zn, and includes seven deposits, among which Wandongshan is the main deposit and occupies approximately 80% of the reserve (He, 2011). Four types of the orebodies, porphyry Cu–Au (P-CA), skarn-type poly-metallic (S-P), magmatic Fe–Au (M-FA) and laterite-type Fe–Au (L-FA) orebodies, are developed in the Wandongshan area.
The Wandongshan deposit has an area of about 4 km². The deposit bedrock includes Middle Triassic Beiya Formation limestone, Lower Tertiary Lijiang Formation sandstone and conglomerate, as well as Quaternary sediments (Fig. 1). The Beiya Formation consists of five members, and the fifth, fourth and third members are well developed in the studied area. Tertiary porphyry intrusions are abundant, and primarily include quartz-monzonite porphyry (QMP), quartz-syenite porphyry (QSP), biotite-K-feldspar porphyry (BKFP) and lamprophyre (Figs. 1, 2). The QMP and QSP intruded the Beiya Formation carbonates in the form of stocks and dikes (Figs. 3, 4). The QMP is widely developed and has an emplacement age of 36.9 ± 0.7 Ma (Lu et al., 2012). The QSP with an age of 34.6 ± 0.5 Ma (Lu et al., 2012) is associated with P-CA and S-P orebodies and partly intruded the QMP. The BKFP intruded the Lijiang Formation lacustrine sedimentary rocks at 3.78 ± 0.02 Ma (40Ar/39Ar plateau age of biotite) (Xu et al., 2007a, b). Lamprophyres occur as dikes and include minette and cuselite. One minette dike has an isotopic age of 59.44 ± 0.30 Ma (40Ar/39Ar plateau age of phlogopite) and a cuselite dike associated with magmatic Fe–Au orebody intruded at 27.81 ± 0.54 Ma (Xu et al., 2007a).

M-FA orebodies are widely developed in the Wandongshan area. Most M-FA orebodies occur as pockets in the contact zone between different intrusions or between the intrusive and the carbonate (called contact M-FA), while some M-FA orebodies occur mainly in the bedding and small steep fractures in the Triassic carbonates (called bedded M-FA) (Figs. 2, 3). Ore minerals in M-FA orebodies are dominated by limonite, hematite and magnetite. The P-CA orebodies occur within the QSP and the S-P orebodies occur in the endoskarn zone (Yang, 2010) developed as the intrusion boundary curves greatly (Figs. 2, 3). In P-

![Diagram](image-url)
CA orebodies, the metallic minerals contain pyrite, chalcopyrite and small amounts of galena and sphalerite; non-metallic minerals include quartz and calcite. The mineral assemblage in the endoskarn consists of garnet, diopside, epidote, chlorite, magnetite and small amounts of pyrite and chalcopyrite. The L-FA orebodies are in Tertiary laterite and formed by the break-up, weathering and re-sedimentation of the primary M-FA orebodies (Figs. 2, 4).

3. Statistical data and analyses

3.1. Raw data

Exploration in the Wandongshan gold poly-metallic deposit has been carried out by the Yunnan Geology and Mineral Resources Co. Ltd. A total of 101 mineralized drillcores, with at least 40 samples in each drillcore, were selected from the exploration report for analysis. Elements Au, Ag, Cu, Pb and Zn are tested in most drillcores; and, in a small number of drillcores plus 11 abstracted sections with at least 40 samples are categorized into 6 groups according to the various mineralizations: S-P mineralization (2 samples), P-CA mineralization (2 samples), M-FA mineralization (15 samples), L-FA mineralization (14 samples), M-FA dominated mineralization (74 samples) and P-CA or S-P dominated mineralization (5 samples). Moreover, the M-FA dominated drillcores are categorized into 3 sub-groups according to the geological positions of M-FA orebodies: contact M-FA (C-M-FA) dominated mineralization (14 samples), contact and bedded M-FA (C+B-M-FA) dominated mineralization (21 samples) and bedded M-FA (B-M-FA) dominated mineralization (39 samples).

3.2. General element distributions

The gold mineralization described in this study is delimited based on a cutoff of 1 g/t, and 2 g/t for Ag, 0.1% for Cu, 0.2% for Pb and 0.4% for Zn. The element concentration curves in multiple-mineralization-type Z1 and laterite-type Z13 are shown in Fig. 5, and the correlation coefficients among elements are listed in Table 1.

Table 1
Correlation coefficients of element concentrations from drillcore samples in the Wandongshan gold poly-metallic deposit, Yunnan, China. (The original data comes from the 3rd Geological Team of the Yunnan Geology and Mineral Resources Co. Ltd., 2006).

<table>
<thead>
<tr>
<th>Drillcore number</th>
<th>Mineralization type</th>
<th>Au–Ag</th>
<th>Au–Cu</th>
<th>Pb–Zn</th>
<th>Drillcore number</th>
<th>Mineralization type</th>
<th>Au–Ag</th>
<th>Au–Cu</th>
<th>Pb–Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z2-P</td>
<td>P-CA</td>
<td>−0.03</td>
<td>0.23</td>
<td>0.20</td>
<td>Z1-M</td>
<td>M-FA</td>
<td>0.28</td>
<td>0.36</td>
<td>0.51</td>
</tr>
<tr>
<td>Z3-P</td>
<td>P-CA</td>
<td>0.87</td>
<td>0.81</td>
<td>0.74</td>
<td>Z2-M</td>
<td>M-FA</td>
<td>0.42</td>
<td>0.14</td>
<td>0.50</td>
</tr>
<tr>
<td>Z11-P</td>
<td>P-CA</td>
<td>0.59</td>
<td>0.27</td>
<td>0.82</td>
<td>Z4-M</td>
<td>M-FA</td>
<td>0.54</td>
<td>0.90</td>
<td>0.89</td>
</tr>
<tr>
<td>Z16-P</td>
<td>P-CA</td>
<td>0.87</td>
<td>0.21</td>
<td>0.53</td>
<td>Z5-M</td>
<td>M-FA</td>
<td>0.06</td>
<td>0.83</td>
<td>0.20</td>
</tr>
<tr>
<td>Z17-P</td>
<td>P-CA</td>
<td>0.65</td>
<td>0.71</td>
<td>0.95</td>
<td>Z6-M</td>
<td>M-FA</td>
<td>0.09</td>
<td>0.06</td>
<td>0.24</td>
</tr>
<tr>
<td>Z1-S</td>
<td>S-P</td>
<td>0.76</td>
<td>0.60</td>
<td>0.85</td>
<td>Z7-M</td>
<td>M-FA</td>
<td>0.94</td>
<td>0.30</td>
<td>0.72</td>
</tr>
<tr>
<td>Z1-S</td>
<td>S-P</td>
<td>0.78</td>
<td>0.70</td>
<td>0.57</td>
<td>Z8-M</td>
<td>M-FA</td>
<td>0.40</td>
<td>0.36</td>
<td>0.51</td>
</tr>
<tr>
<td>Z16-S</td>
<td>S-P</td>
<td>0.57</td>
<td>0.50</td>
<td>0.19</td>
<td>Z13</td>
<td>L-FA</td>
<td>−0.25</td>
<td>0.43</td>
<td>0.79</td>
</tr>
<tr>
<td>Z17-S</td>
<td>S-P</td>
<td>0.91</td>
<td>0.75</td>
<td>0.93</td>
<td>Z15</td>
<td>L-FA</td>
<td>0.42</td>
<td>0.33</td>
<td>0.88</td>
</tr>
</tbody>
</table>

M-FA: magmatic Fe–Au; P-CA: porphyry Cu–Au; S-P: skarn-type poly-metallic; L-FA: laterite-type Fe–Au.

Table 2
Hurst exponents (H) and correlation dimensions (D2) of vertical distributions of ore-forming elements in typical drillcores in the Wandongshan deposit, Yunnan, China.

<table>
<thead>
<tr>
<th>Drillcore number</th>
<th>Mineralization type</th>
<th>H</th>
<th>D2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z1</td>
<td>C + B-M-FA dominated</td>
<td>0.81</td>
<td>0.51</td>
</tr>
<tr>
<td>Z2</td>
<td>C + B-M-FA dominated</td>
<td>0.80</td>
<td>0.51</td>
</tr>
<tr>
<td>Z3</td>
<td>P-CA or S-P dominated</td>
<td>0.70</td>
<td>0.73</td>
</tr>
<tr>
<td>Z4</td>
<td>C-M-FA dominated</td>
<td>0.74</td>
<td>0.77</td>
</tr>
<tr>
<td>Z5</td>
<td>C + B-M-FA dominated</td>
<td>0.77</td>
<td>0.73</td>
</tr>
<tr>
<td>Z6</td>
<td>B-M-FA dominated</td>
<td>0.75</td>
<td>0.73</td>
</tr>
<tr>
<td>Z7</td>
<td>C + B-M-FA dominated</td>
<td>0.70</td>
<td>0.72</td>
</tr>
<tr>
<td>Z8</td>
<td>B-M-FA dominated</td>
<td>0.74</td>
<td>0.87</td>
</tr>
<tr>
<td>Z9</td>
<td>B-M-FA dominated</td>
<td>0.64</td>
<td>0.54</td>
</tr>
<tr>
<td>Z10</td>
<td>C + B-M-FA dominated</td>
<td>0.78</td>
<td>0.73</td>
</tr>
<tr>
<td>Z11</td>
<td>C + B-M-FA dominated</td>
<td>0.70</td>
<td>0.60</td>
</tr>
<tr>
<td>Z12</td>
<td>C + B-M-FA dominated</td>
<td>0.79</td>
<td>0.60</td>
</tr>
<tr>
<td>Z13</td>
<td>L-FA</td>
<td>0.69</td>
<td>0.78</td>
</tr>
<tr>
<td>Z14</td>
<td>B-M-FA dominated</td>
<td>0.78</td>
<td>0.72</td>
</tr>
<tr>
<td>Z1-M</td>
<td>M-FA</td>
<td>0.81</td>
<td>0.72</td>
</tr>
<tr>
<td>Z2-M</td>
<td>M-FA</td>
<td>0.87</td>
<td>0.72</td>
</tr>
<tr>
<td>Z4-M</td>
<td>M-FA</td>
<td>0.72</td>
<td>0.72</td>
</tr>
<tr>
<td>Z5-M</td>
<td>M-FA</td>
<td>0.84</td>
<td>0.72</td>
</tr>
<tr>
<td>Z6-M</td>
<td>M-FA</td>
<td>0.81</td>
<td>0.72</td>
</tr>
<tr>
<td>Z7-M</td>
<td>M-FA</td>
<td>0.75</td>
<td>0.72</td>
</tr>
<tr>
<td>Z8-M</td>
<td>M-FA</td>
<td>0.66</td>
<td>0.72</td>
</tr>
<tr>
<td>Z16-S</td>
<td>S-P</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Z17-P</td>
<td>P-CA</td>
<td>0.73</td>
<td>0.75</td>
</tr>
<tr>
<td>Z3-P</td>
<td>P-CA</td>
<td>0.76</td>
<td>0.75</td>
</tr>
</tbody>
</table>

M-FA: magmatic Fe–Au; P-CA: porphyry Cu–Au; S-P: skarn-type poly-metallic; L-FA: laterite-type Fe–Au; C + B-M-FA dominated: drillcores dominated by contact M-FA mineralization; C + B-M-FA dominated: drillcores dominated by contact and bedded M-FA mineralization; B-M-FA dominated: drillcores dominated by bedded M-FA mineralization; P-CA or S-P dominated: drillcores dominated by P-CA or S-P mineralization.
The concentrations of Au, Ag, Cu, Pb and Zn in Fe-dominated areas (limonite–magnetite) are greater and show higher fluctuations than those in skarns and QSP (Fig. 5a). The five elements display relatively distinct distributions in Fe-dominated areas and laterite, as shown in Fig. 6 the correlations of Au vs. Ag, Au vs. Cu and Pb vs. Zn in Z1-M and Z13 are low. Most element correlations in most M-FA drillcores are low (Table 1). Additionally, element correlations in the P-CA or S-P drillcores vary largely (Figs. 5, 6; Table 1).

4. Mathematical models and calculation process

The element distributions in different mineralized areas were analyzed using (a) H calculated by R/S analysis and (b) multifractal parameters estimated by the box-counting method (BCM).

4.1. R/S analysis

The R/S analysis is the one of the most popular methods to calculate H. The calculation starts with a whole concentration sequence $\{\xi_i\}_{i=1}^{n}$ that is covered by a box with length $e$, and then the mean is calculated over the available data in the range $e$.

$$\langle E\xi\rangle_e = \frac{1}{n} \sum_{i=1}^{n} \xi_i$$

Summing up the differences from the mean to get the cumulative total at each data point, $X(i, n)$, from the beginning up to any point of the box, then we have:

$$X(i, e) = \sum_{i=1}^{i} \left[ \xi_i - \langle E\xi\rangle_e \right] = \sum_{i=1}^{i} \xi_i - i\langle E\xi\rangle_e, \quad 1 \leq i \leq n.$$  

The range $R(e)$ is calculated from the difference between the maximum $X(i, e)$, max $X(i, e)$, and the minimum $X(i, e)$, min $X(i, e)$:

$$R(e) = \max X(i, e) - \min X(i, e), \quad 1 \leq i \leq e.$$
The range, $R(e)$, is divided by the standard deviation $S(e)$

$$S(e) = \left\{ \frac{1}{n} \sum_{i=1}^{n} [\xi_i - (E\xi_i)]^2 \right\}^{1/2}$$

and the obtained result is called the rescaled range $R/S$.

The whole concentration sequence can usually be covered by several non-overlapping boxes with length $e$. After determining $R/S$ for each box, we can get the mean value of $R/S$, i.e., $E(R/S)$. Using successively shorter $e$ and finding the $E(R/S)$ of these boxes, we can obtain $H$ according to the following equation:

$$\ln E(R/S)_e = \ln C + H \ln e$$

(5)

where $C$ is a constant.

The expected values of $H$ lie between 0 and 1. Values of $H \approx 0.5$, $0 < H < 0.5$ and $0.5 < H < 1$ indicate random, anti-persistent and persistent distributions, respectively (Wang et al., 2011a; Zuo et al., 2009).

4.2. Multifractal model

The traditional partitioning approach in the moment-based multifractal model is BCM. In the BCM, a concentration sequence of length $N$ is divided into $n(e)$ non-overlapping boxes with size $e$ (Halsey et al., 1986) and the measurement ($\mu_j$) in each box is calculated from:

$$\mu_j = \frac{m_j}{m_l} = \frac{m_j}{\sum_{j=1}^{n(e)} m_j}$$

(6)
where \( m_j \) is the sum of the concentrations in box \( j \), \( m_T \) is the sum of the total concentrations of the data, and \( n(\varepsilon) = N/\varepsilon \). Then, the partition function \( \chi(q, \varepsilon) \) is defined as:

\[
\chi(q, \varepsilon) = \sum_{j=1}^{n(\varepsilon)} \left[ \frac{m_j}{\sum_{j=1}^{n(\varepsilon)} m_j} \right]^{q-1}
\]

(7)

where

\[
X_j(q, \varepsilon) = \left( \frac{m_j}{\sum_{j=1}^{n(\varepsilon)} m_j} \right)^{q-1}.
\]

(8)

The moment \( q \) provides a much more accurate and detailed way for exploring different regions with the singular measure. For \( q > 1 \) and \( q < 1 \), \( \mu^q \) amplifies greater concentrations and smaller concentrations respectively.

The mass exponent \( \tau(q) \) for moment \( q \) can be written as (Hentschel and Procaccia, 1983):

\[
\tau(q) = \lim_{\varepsilon \to 0} \frac{\log(\chi(q, \varepsilon))}{\log(\varepsilon)}
\]

(9)

The generalized dimension \( D_q \) can then be introduced through the following scaling relationship (Feder, 1989; Hentschel and Procaccia, 1983):

\[
D_q = \lim_{\varepsilon \to 0} \frac{\log[\chi(q, \varepsilon)]}{(q-1) \log(\varepsilon)}
\]

(10)

The moment \( q \) and corresponding \( D_q \) compose a Rényi spectrum. Greater variation of \( D_q \) with respect to \( q \) implies a higher heterogeneity of a space (Arias et al., 2011). In the case of \( q = 1 \), \( D_1 \) is defined as the limit \( D_1 = \lim_{\varepsilon \to 1} D_q \) and named information dimension; when \( q = 2, D_2 \) is equal to \( \tau(2) \) and is correlation dimension. The \( D_2 \) of a space with a more compact distribution is greater than that characterized by an isolated distribution (Durga Bhavani et al., 2008).

The singularity exponent \( \alpha(q) \) and the corresponding fractal dimension \( f(\alpha) \) can be obtained by a Legendre transform as:

\[
\alpha(q) = \frac{d\tau(q)}{dq}
\]

(11)

\[
f(\alpha) = q\alpha(q) + \tau(q) = q \frac{d\tau(q)}{dq} - \tau(q).
\]

(12)

The \( \alpha(q) \) and the corresponding \( f(\alpha) \) compose a multifractal spectrum with an inverse bell shape. A wider multifractal spectrum suggests a more heterogeneous concentration sequence, and vice versa.

4.3. Calculation process and case analysis

The calculations of \( H \) for the distributions of Au, Ag and Pb in Z1 show high goodness-of-fit between \( e \) and \( E(R/S) \). (Fig. 7a). The values of \( H \) for most element distributions in Z1-M are greater than those in Z3-P, Z1-S and Z15 (L-FA) (Fig. 7b). Yet, for Pb, the \( H \) in Z1-S and Z15 is greater than that in Z1-M.

The multifractal spectrum is calculated with \( q \) ranging from \(-2\) to \(2\) with intervals of \(0.2\). In calculation, plots of \( \ln(\chi(q, \varepsilon)) \) vs. \( \ln(\varepsilon) \) show good straight line fits, e.g., for Au in Z1 (Fig. 8a). The moment \( q \) shows an increase with \( \tau(q) \) (Fig. 8b) and a decrease with \( D_q \) and \( \alpha(q) \) (Fig. 8c, d), supporting their multifractal nature. The multifractal spectra for element distributions in Z1-M are wider than those in Z3-P and Z1-S, and the spectrum for Au in Z15 is wider than that in Z1-M (Fig. 9). Additionally, the multifractal spectra for Au and Cu are somewhat wider than for...
the other elements. The analysis for the four selected drillholes shows that fractal parameters are valid for distinguishing various mineralizations and drillcores. Furthermore, the $D_2$, $a(2)$ and $f(2)$ for element distributions exhibit obvious positive correlation with each other in all drillcores, with correlation coefficients greater than 0.97 (Fig. 10), so $D_2$ is selected for following analysis.

5. Results of analysis

5.1. Fractal parameters for various ore types

5.1.1. Comparison of different single-type mineralized drillcores

In order to discuss controls of ore type on element distributions, the characteristics of element distributions in P-CA, S-P, M-FA and L-FA drillcores are analyzed. The ranges of $H$ or $D_2$ for the elements studied in P-CA drillcores are narrower than those in M-FA or L-FA drillcores (Fig. 11), reflecting that element distributions in different P-CA mineralized areas are similar, whereas those in M-FA or L-FA mineralized areas are heterogeneous. One exception is that the $D_2$ range for Ag in P-CA drillcores is wide owing to a very low $D_2$ in Z2-P, which is caused by the extremely high concentrations of this element in the section.

The means of $H$ values for Au, Ag, Cu and Zn in M-FA drillcores are higher than those in P-CA, S-P or L-FA drillcores, suggesting a relatively high persistence of M-FA mineralization in the Wandongshan deposit. This corresponds to the result derived from the $H$ analysis for the typical drillcores. The means of $D_2$ values for Au, Ag, Cu, Pb and Zn in P-CA or S-P drillcores are greater than those in M-FA or L-FA drillcores, indicating that high element concentrations are more compact in P-CA or S-P mineralized areas.

5.1.2. Comparison between single-type and multi-type mineralized drillcores

For deducing the roles of spatial co-existence of multi-type mineralizations on element distributions, comparison of fractal parameters in single-type mineralized drillcores and in multi-type mineralized drillcores is carried out.

The ranges of $D_2$ for Au, Ag, Cu and Pb in M-FA dominated drillcores are wider than those in M-FA or L-FA drillcores (Fig. 11). The means of $H$ in M-FA dominated drillcores are higher than those in M-FA or L-FA drillcores; whereas $D_2$ has an opposite trend, revealing stronger persistent element distributions and weaker compactness (or more isolated) of high element concentrations in M-FA dominated drillcores. As for P-CA or S-P dominated drillcores, the ranges of $D_2$ values are narrower than those in M-FA drillcores and wider than those in P-CA or S-P drillcores. The means of $H$ values in P-CA or S-P dominated drillcores are higher than those in P-CA or S-P drillcores; while $D_2$ shows an inverse relationship, representing stronger persistent element distributions and weaker compactness of high element concentrations in P-CA or S-P dominated drillcores. This indicates that the spatial co-existence of multi-type mineralizations can lead to stronger persistent element distributions and weaker compactness of high element concentrations.

The ranges of $H$ or $D_2$ values in M-FA dominated drillcores are wider than those in P-CA or S-P dominated drillcores; and the means of $H$ values are higher than those in P-CA or S-P dominated drillcores; while the $D_2$ of Au, Ag and Zn has an opposite trend, suggesting that
high concentrations of Au, Ag, Cu, Pb and Zn are more compact in M-FA dominated drillcores (Fig. 11).

Moreover, the means of \( D_2 \) values in C-M-FA and C+B-M-FA dominated drillcores are greater than those in B-M-FA dominated drillcores (Fig. 11).

5.2. Fractal parameters for the different elements

The mean of \( H \) for Au is lower than for the other elements in M-FA, L-FA and M-FA dominated drillcores, revealing a weaker persistent Au distribution (Fig. 11). The means of \( D_2 \) values for Au, Ag and Cu are greater than those for Pb and Zn in M-FA, M-FA dominated and P-CA or S-P dominated drillcores, indicating that high concentrations of Au, Ag or Cu are more compact than high concentrations of Pb or Zn.

The relationships of \( H \) values for Au vs. Ag, Au vs. Cu and Pb vs. Zn are quite weak in M-FA dominated, P-CA or S-P dominated and L-FA drillcores, while those of \( D_2 \) values are relatively strong (Table 3, Fig. 12). The \( D_2 \) values for Pb show obvious positive correlation (correlation coefficients no less than 0.8) with those for Zn in M-FA dominated, P-CA or S-P dominated and L-FA drillcores (Fig. 12c). The values of \( D_2 \) for Au vs. Ag and Cu have a correlation coefficient of 0.75 in M-FA dominated drillcores, 0.35 in P-CA or S-P dominated drillcores and 0.81 in L-FA dominated drillcores (Fig. 12a). The correlation coefficients of \( D_2 \) values for Au vs. Cu are 0.84, 0.66 and 0.83 in M-FA dominated, P-CA or S-P dominated and L-FA drillcores, respectively (Fig. 12b). It is revealed that Au and Cu as well as Pb and Zn exhibit similar spatial distributions in M-FA or L-FA drillcores, and only Pb and Zn have similar spatial distributions in P-CA or S-P orebodies.

5.3. Spatial distributions of mathematical parameters

The variance of fractal parameters in exploration lines 1 and 2 is shown in Figs. 3 and 4. In Fig. 3, from the center of QSP (Z3) to the Triassic carbonates (Z9), with the dominant mineralization changing from P-CA to M-FA and the M-FA orebody from contact type to bedded type, the values of \( H \) for Au, Ag, Cu, Pb and Zn increase firstly and then decrease. The values of \( H \) for Au and Cu decrease at Z13 (L-FA), whereas those of Pb and Zn increase at Z13. The mineralization type is dominated by M-FA with different shapes in exploration line 2 (Fig. 4). From the contact zone (Z7) to the Triassic carbonates (Z8 or Z6), the values of \( H \) for Au, Ag, Cu, Pb and Zn decrease. However, the values of \( H \) for Au and Ag in Z7 are relatively low due to the existence of extremely high concentrations. It is concluded that the element distributions exhibit stronger persistence in contact areas than in the center of QSP and the distal Triassic carbonates.

From the QSP center to Triassic carbonates, the values of \( D_2 \) for ore-forming elements decrease generally (Fig. 3), exception for Ag and Zn in Z2 due to existence of extremely high values. In Fig. 4, from the contact area to Triassic carbonates (from Z7 to Z8 or Z6), the values of \( D_2 \) for ore-forming elements decrease.

The spatial distribution of \( D_2 \) values for Au in M-FA dominated drillcores is shown in Fig. 13. It shows that the outline determined by the C-M-FA and C+B-M-FA dominated drillcores is very wavy. Most of the B-M-FA dominated drillcores are outside of the outline. The widely spread B-M-FA mineralization reveals a high-energy transportation of ore-forming fluid. Most high \( D_2 \) values are clustered in the SE corner of the outline, suggesting an ore-forming preference in space. It is revealed that the high concentrations of ore-forming elements are more compact mostly in contact areas than in distal Triassic carbonates, in which high...
concentrations of ore-forming elements are isolated. It is further verified that the geological position controls the geometric shape (especially for M-FA) of the orebodies and the element distributions.

6. Discussions

6.1. Controls on element distribution

According to the Hurst exponents and the correlation dimensions, the distributions of ore-forming elements in P-CA or S-P dominated drillcores often have weaker persistence but stronger compactness of high concentrations than those in most M-FA dominated drillcores, and the variance of mathematical parameters in different P-CA or S-P dominated drillcores is small. This finding can be explained by the more local ore-forming fluid activity associated with porphyry and skarn mineralizations compared to magmatic Fe–Au mineralization.

For the formation of P-CA or S-P orebodies, ore-bearing fluid penetrates into porous rocks and deposits metals in small interconnected voids evenly and narrowly distributed in the rocks. For the formation of M-FA orebodies, ore-bearing fluid is transported via interconnected fractures in a very large space, resulting in strongly persistent element distributions and isolated high concentrations. As a result of multiple tectonic deformations and complex geological structures, the shape and size of fractures and contact void containing M-FA orebodies are spatially varied, inducing heterogeneous element distributions in different locations. The distributions of ore-forming elements in L-FA drillcores vary in different areas owing to the heterogeneous element distributions in the primary M-FA orebodies and the complex sediment process in weathering.

In vertical cross-sections, the elements studied exhibit stronger persistent distributions and weaker compactness of high element concentrations in most contact areas than in the center of the QSP. Further, in distal Triassic carbonates, the elements often exhibit weakly persistent distributions and isolated occurrences of high element concentrations. This reflects that the contact mineralization areas were beneficial for developing pocket M-FA orebodies, resulting in stronger persistent element distributions and weaker compactness of high element concentrations. In the distal Triassic carbonates, the bedded or vein M-FA orebodies were likely formed with interruptions because the ore-forming fluid has lower temperature and pressure or lower gold enrichment after transportation, inducing weakly persistent element distribution and isolated occurrences of high element concentrations.

It is further shown that the spatial co-existence of multi-type mineralizations can cause strongly persistent element distributions and weakly compact distributions of high element concentrations. Ore...
type, geological position and the spatial co-existence of multi-type mineralizations are suggested to be the main factors affecting the vertical element distribution in the Wandongshan deposit.

6.2. Associations of ore-forming elements

The vertical distributions of Au, Ag and Cu, as well as Pb and Zn, generally display distinct distributions in M-FA and L-FA orebodies; whereas the $D_2$ values for Au vs. Cu and Pb vs. Zn exhibit positive correlations. These reflect the fact that, during fluid transportation, the ore-forming elements were deposited in different areas in response to changes in physical and chemical conditions, resulting in their distinct distributions. However, the spatial distributions of the studied ore-forming elements are similar, partly due to their related elemental behaviors. In P-CA and S-P orebodies, only Pb and Zn show positive correlation in $D_2$ values. This verifies that the chemical systems for M-FA mineralization and for P-CA or S-P mineralization are different.

7. Conclusions

(1) In the Wandongshan gold poly-metallic deposit, the elements Au, Ag, Cu, Pb and Zn exhibit stronger persistent distributions and weaker compactness of high concentrations in magmatic Fe–Au orebodies than in porphyry Cu–Au or skarn-type poly-metallic orebodies, which were likely the result of the different types of transportation and deposition of ore-bearing fluids. The quantified element distribution features of the Wandongshan gold poly-metallic deposit show that the magmatic Fe–Au orebodies serve as the most economic mineralization in the Beiya orefield.

(2) The ore type, geological position and spatial co-existence of multi-type mineralizations are the main factors affecting the vertical element distribution in the Wandongshan gold deposit. The spatial co-existence of different types of mineralization caused strongly persistent element distributions, weakly compact distributions of high element concentrations and better continuity of mineralization. The geological contact is the most important container of magmatic Fe–Au ores, where high element concentrations are often compact; and the long-distance ore-forming fluid transportation along bedding fault induces wide development of Fe–Au ores.

(3) In the Wandongshan gold poly-metallic deposit, the correlations of $D_2$ for Au vs. Cu and Pb vs. Zn in the magmatic Fe–Au dominated and L-FA drillcores are high, suggesting that Au and Cu have similar distribution patterns, and Pb and Zn have similar distribution patterns. In porphyry Cu–Au and skarn-type poly-metallic orebodies, only Pb and Zn exhibit similar spatial distributions. This verifies that the magmatic Fe–Au mineralization has a different chemical system compared to porphyry Cu–Au or skarn-type poly-metallic mineralization.

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