RESEARCH ARTICLE

Multifractal characteristics of gold grades series in the Dayingezhuang Deposit, Jiaodong Gold Province, China

L. Wan [1,2] · Y. Q. Zhu [1] · X. C. Deng [1,2]

Abstract In the paper, the multifractal detrended fluctuation analysis is used to investigate the multifractal characteristics of gold grades series in the Dayingezhuang gold deposit, Jiaodong province, China. Results obtained from the multifractal parameters and multifractal spectra show that the gold grades series exhibit multifractal scaling and different long-range correlations. The asymmetry of multifractal spectrum shows that the range of the right-side branches of the multifractal spectrum is larger than that of the left-side branches for the gold grades series of intensely mineralized drifts, but the gold grades series of the barely mineralized zones is on the contrary, which indicates that the shape of of multifractal spectrum may provide directions in the study of ore-forming potential. Moreover, we analyze the sources of multifractality quantifying the contributions of two factors, the long-range correlations and the broad fat-tail distributions. We find that the multifractality structure of gold grades series is due to both long-range correlation and the fat-tail probability density function, but the former is greater attributed to the latter.

Keywords Multifractal · Detrended fluctuation analysis · Gold grade · Fat-tail probability distribution · Long-range correlation · Mineralization intensity

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Introduction

Fractal is an important branch of nonlinear. In particular, fractal, developed to extract qualitative and quantitative information from time series, have been applied recently to the study of a large variety of irregular, erratic signals and by now have demonstrated to be very useful to reveal deep dynamical features (Telesca et al. 2004; Monecke et al. 2005). A monofractal object has only one scaling exponent. Monofractals are homogeneous objects, in the sense that they have the same scaling properties, characterized by a single singularity exponent. A multifractal object requires many indices to characterize its scaling properties. Multifractals can be decomposed into many-possibly infinitely many sub-sets characterized by different scaling exponents (Mandelbrot 1983). Thus, multifractals are intrinsically more complex and inhomogeneous than monofractals, and characterize systems featured by very irregular dynamics, with sudden and intense bursts of high frequency fluctuations (Davis et al. 1994).

The multifractal is also applied to study the distributions of various geological objects, such as rock fractures (Agterberg et al. 1996) and geochemical data and as a powerful tool in the discrimination of Geological Phenomena (Deng et al. 2008a, b; Panahi and Cheng 2004). In the past two decades, several multifractal models supported by geographic information system (GIS) have been developed and successfully applied to the study of the distribution of mineralization (Deng et al. 2009, 2011; Agterberg 2007; Cheng and Agterberg 2009; García Moreno et al. 2008; Peitgen et al. 1992; Turcotte 1997). These multifractal models are based upon the standard partition function multifractal formalism, which has been developed for the multifractal characterization of normalized, stationary measures (Feder 1988). But, this standard formalism does not give correct results for nonstationary time series

that are affected by trends or that cannot be normalized. Recently, Kantelhardt et al. proposed an alternative approach the multifractal detrended fluctuation analysis (MF-DFA), based on a generalization of the detrended fluctuation analysis method (DFA) and the identification of scaling of the qth-order moments depending on the sample length. Since, often experimental data are affected by nonstationarities like trends, which have to be well-distinguished from the intrinsic fluctuations of the system in order to find the correct scaling behavior of the fluctuations. In addition, we do not know the reasons for underlying trends in collected data and even worse we do not know the scales of the underlying trends, also, usually the available record data is small (Kantelhardt et al. 2002). It was basically devised for the analysis of nonstationary time series by incorporating with a detrending procedure. It has also been concluded that the MF-DFA should be recommended for a global detection of multifractal behavior.

Because geochemical field are of multifractal features, and exhibit non symmetric multifractal spectra, which are considered to be a natural result that geochemical fields have inevitably undergone a certain degree of local superimposition or other modifications in their long history of development. The aim of this paper is to investigate the multifractal characteristics of gold grades series and to distinguish the ranks of mineralization intensity, using multifractal detrended fluctuation analysis techniques, in area of the Dayingezhuang disseminated-veinlet gold deposit located in the Jiaodong gold province, China.

Data and methods

Deposit geology and data acquisition

The Dayingezhuang ore deposit is located in the middle segment of the Zhaoping fault zone in Jiaodong gold province, China. The gold deposits in the northwestern part of the Jiaodong Peninsula are divided into two types: quartz vein type and disseminated-veinlet type. The disseminated-veinlet type is dominant in the Jiaodong gold province (Fig. 1) (Deng et al. 2006, 2008b; Qiu et al. 2002; Yang et al. 2006). The quartz vein type deposit has a smaller reserve and higher grade, whereas the disseminated-veinlet deposit has a larger reserve and lower grade. The disseminated-veinlet type gold deposits are mainly controlled by major faults and the quartz vein type gold deposits are mainly controlled by secondary faults that occur with some distances away from the major faults (Deng et al. 2008b, 2011), and the gold ore deposit is with 3000 m in length, 30 m~140 m in width; moreover, ore bodies of altered rocks extend like sloping wave in a strike and in trend. The reserves of the Dayingezhuang are more

than 100 t, with an estimated annual production greater than 2.6 t.

Wallrocks comprise both metamorphosed Precambrian sequences and Mesozoic intrusions. A cataclastic altered zone in the footwall of the Zhaoping fault controls the occurrences of gold mineralization. Wallrock alteration related to gold mineralization consists of K-feldspar alteration, silicification, sericitization, chloritization, phyllic alteration, sericite-quartz alteration and carbonatization. The degree of fracturing and alteration gradually weakens away from the Zhaoping fracture plane.

The wallrocks of the deposit comprise both the metamorphosed Precambrian sequences and the Mesozoic intrusive rocks, i.e., the Linglong granite and different kinds of dikes. The hanging wall of the Zhaoping fault is composed of metamorphic rocks of the Jiaodong group with weak alteration and gold mineralization. The cataclastic zone in the immediate footwall is intensely altered and hosts the main orebodies of the Dayingezhuang gold deposit. Generally, the mineralization in the immediate footwall of the Zhaoping fault is characterized by strong silicification, sericitization, sulfidation and K-feldspar alteration. More than 20 alteration zones of different sizes occur in the footwall of the Zhaoping fault zone. In the deposit, No. I and II altered zones are the biggest. The No. II altered zone is located between drift 64 and drift 89 in the northern part of the deposit, and includes 73 orebodies, in which the No. II-1 orebody is the greatest. The No. II-1 orebody extends from −26 to −492 m within drift 66 and drift 88, with a cut-off grade of 2 g/t. The main exploration levels include −140, −175, −210 and −290, etc. (Deng et al. 2008a, b). This paper focuses on the analysis of the mineral intensity on −282, −290 and −210 m, in the No. II-1 orebody and surrounding alteration zone.

Variation of gold grades in different drifts reflects structural variations such as the size and abundance of fractures or microfractures at different locations within the fault system. Based on variation in mineralization density, the drifts are classified into the three rank: (I) barely mineralized drifts, in which the proportion of gold grades is greater than 1 g/t and lower than 20 %, and the orebodies are barely developed; (II) moderately mineralized drifts, in which the proportion of gold grades is greater than 1 g/t and between 30 % and 60 %, and the mineralization is relatively intermittent and thin; (III) intensely mineralized drifts, in which the proportion of gold grades is not less than 1 g/t and larger than 60 %, and the mineralization is very thick (Deng et al. 2011).

The gold data are obtained the continuous channel samples with 1 m in the selected drifts at different levels in orebody II-1 along different drifts on −290, −282 and −210 m levels. The lengths of all 12 samples (denoted as S1 to S12) are greater than 100 m. The histograms of gold grades (form S1 to S12) in different drifts are illustrated in Fig. 2.

Fig. 1 Generalized geological map of the western part of the Jiaodong gold province, China
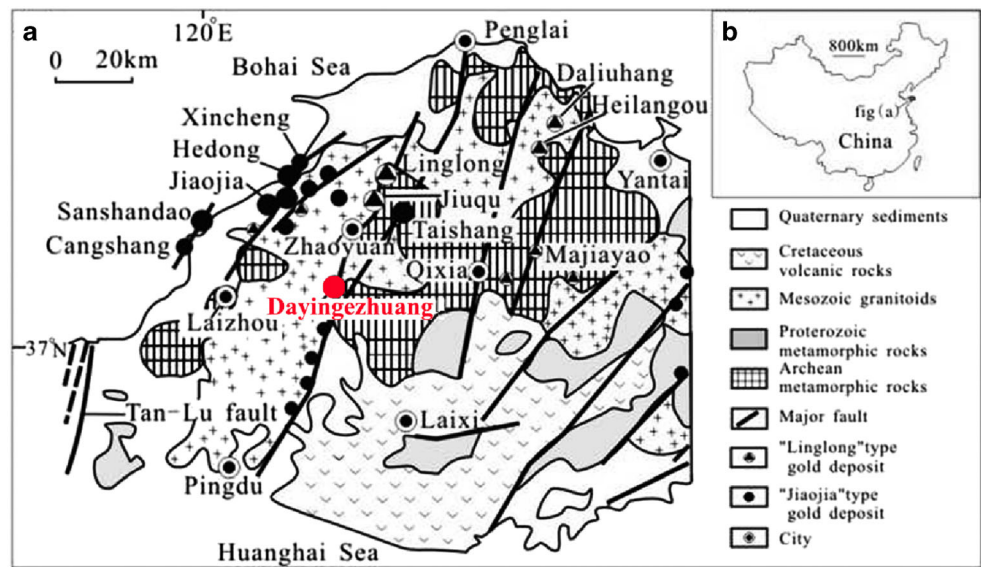
Multifractal detrended fluctuation analysis method (MF-DFA)

The multifractal detrended fluctuation analysis method (MF-DFA) is the extension of the detrended fluctuation (DFA) method which is used to compute the roughness exponent of monofractal signals and for the identification of long range correlations in non-stationary time series (Kantelhardt et al. 2002). This method applied to our experimental data can be summarized as follows:

Let us suppose that $\{x_i\}(i=1,2,\ldots,N)$ is a series of length N, and this series is of compact support. Calculate the cumulative sum

$$y(i) = \sum_{k=1}^{i} [x_k - \langle x \rangle], \quad i = 1, 2, \cdots, N \tag{1}$$

where $\langle x \rangle$ represents the average value. Divide the profile $y(i)$

into $N_s = \text{int}(N/s)$ nonoverlapping segments of equal length s. Since length N of the series is often not a multiple of the considered scale s, a short part at the end of the series may remain. In order not to disregard this part of the series, the same procedure is repeated starting from the opposite end. Thereby, $2N_s$ segments are obtained altogether.

Calculate the local trend for each of the $2N_s$ segments by a least-square fit of the series. Then determine the variance

$$F^2(s,v) = \frac{1}{s} \sum_{i=1}^{s} \{y[(v-1)s+i] - y_v(i)\}^2, \quad v = 1, 2, \cdots, N_s \tag{2}$$

and when $v = N_s +1$, $N_s +2, \ldots, 2N_s$, that

$$F^2(s,v) = \frac{1}{s} \sum_{i=1}^{s} \{y[N-(v-N_s)s+i] - y_v(i)\}^2, \tag{3}$$
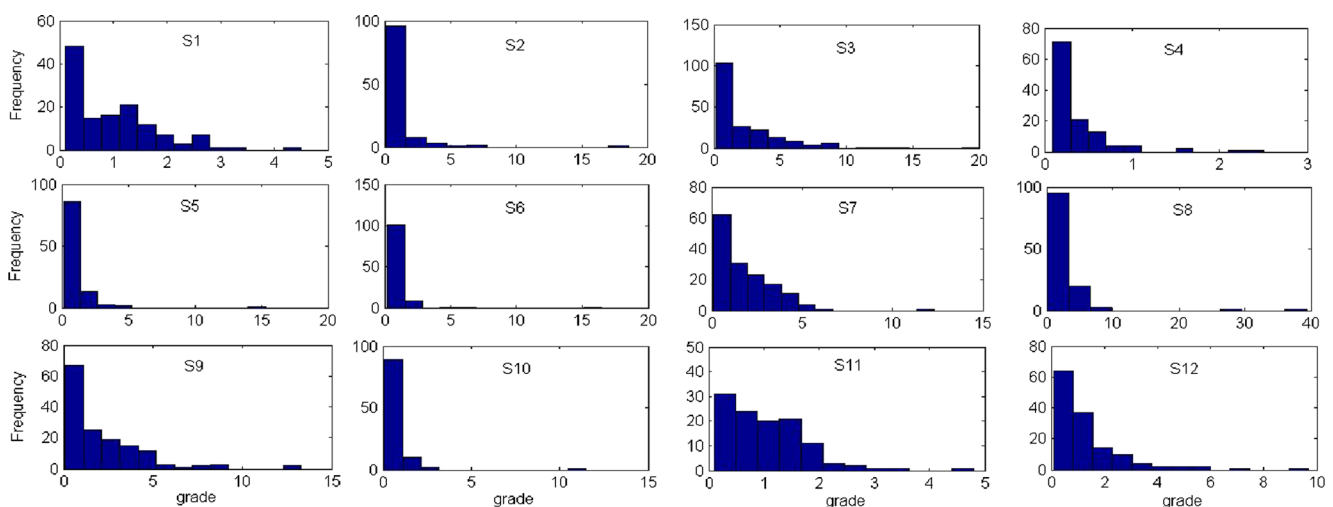
Fig. 2 Histograms of gold grades from S1 to S12

which corresponds to a measure of the second moment for segment v. Here, $y_v(i)$ is the fitting polynomial in segment v, The m-th order polynomials can be used in the fitting procedure (conventionally called m-th order of MFDFA) . The polynomial trend are linear when $m=1$, quadratic when $m=2$, and cubic when $m=3$ (Norouzzadeh and Rahmani 2006).We then define a qth-order fluctuation function,

$$F_q(s) = \left\{ \frac{1}{2N_s} \sum_{v=1}^{2N_s} \left[F^2(s, v) \right]^{q/2} \right\}^{1/q}. \tag{4}$$

Where $q \neq 0$, in general, the index variable q can take any real value except zero.

The scaling of the fluctuation for moment q follows

$$F_q(s) \propto s^{h(q)}. \tag{5}$$

Determine the scaling behavior of the fluctuation functions by analyzing log-log plots of $F_q(s)$ versus s for each value of q.

When $q=0$, the value of $h(0)$, which corresponds to the limit $h(q)$ for $q \rightarrow 0$, cannot be determined directly using the averaging procedure in Eq.(4) because of the diverging exponent. Instead, a logarithmic averaging procedure has to be employed,

$$F_0(s) = \lim_{q \rightarrow 0} F_q(s) = \exp \left\{ \frac{1}{4N_s} \sum_{v=1}^{2N_s} \left[\ln F^2(s, v) \right] \right\}, \tag{6}$$

In general, the exponent $h(q)$ in Eq. (6) may depend on q. For stationary time series, $h(2)$ is identical to the well-known Hurst exponent H (Kantelhardt et al. 2002). Thus, we will call the function $h(q)$ generalized Hurst exponent. Thus, for positive values of q, $h(q)$ describes the scaling behavior of the segments with large fluctuations. On the contrary, for negative values of q, $h(q)$ describes the scaling behavior of the segments with small fluctuations.

From Eqs. (4) and (5), we obtain

$$\frac{1}{2N_s} \sum_{v=1}^{2N_s} \left[F^2(s, v) \right]^{q/2} \propto s^{qh(q)}, \tag{7}$$

and therefore

$$\sum_{v=1}^{N_s} \left[F^2(s, v) \right]^{q/2} \propto s^{qh(q)-1}. \tag{8}$$

For monofractal time series which are characterized by a single exponent over all scales, $h(q)$ is independent of q, whereas for a multifractal time series, $h(q)$ varies with q. This dependence is considered to be a characteristic property of multifractal processes. The $h(q)$ obtained from MF-DFA is

related to the Rényi exponent $\tau(q)$ by

$$qh(q) = \tau(q) + 1, \tag{9}$$

Therefore, another way to characterize a multifractal series is the singularity spectrum $f(\alpha)$ defined by Mandelbrot (Mandelbrot 1983).

$$\tau(q) = qh(q)-1 \tag{10}$$

and then the Legendre transform

$$\alpha(q) = \frac{d\tau(q)}{dq} \text{ and } f(\alpha) = q[\alpha - h(q)] + 1. \tag{11}$$

Where α is the Hölder exponent or singularity strength which characterizes the singularities in a time series. The shape and the singularity spectrum of $f(\alpha)$-curve contain significant information about the distribution characteristics of the examined data set. In general, the spectrum has a concave downward curvature, with a range of α-values increasing correspondingly to the increase in the heterogeneity of the distribution. The values of α_{min} and $f(\alpha_{min})$ can be obtained when the moment q is maximal; α_{man} and $f(\alpha_{ma})$ are derived when q is minimal. The widths of the left and right branches in the multifractal spectrum can be defined by the following equations:

$$\Delta\alpha_L = \alpha_0 - \alpha_{min} \text{ and } \Delta\alpha_R = \alpha_{max} - \alpha_0 \tag{12}$$

Here, α_0 is the special value of α, the Hölder exponent, that corresponds to $q=0$ in the method of moments and maximizes $f(\alpha)$.

Obviously, richer multifractality corresponds to higher variability of $h(q)$. Then, the multifractality degree can be quantified by

$$\Delta h = h(q_{min}) - h(q_{max}) \tag{13}$$

Results and discussion

Table 1 illustrates some of the main descriptive statistics for gold grades series of all 12 samples. According to data in Table 1, most of the kurtosis values are higher than 3 except S1; the positively skewness values are showed from S1 to S12. For the JB test, the null hypothesis is no rejection to a normal distribution. But the results of the JB test show that, at the 0.05 significant level, the JB-values are beyond a critical value. So we can reject the null hypothesis. So, the probability distribution function of variations shows a high degree of peakness and fat tails relative to a normal distribution. Thus, there is a clear departure from Gaussian normality.

MF-DFA is carried out over the returns derived from the twelve gold grades series of grades. The $F_q(s)$ is calculated by

Table 1 Results obtained from the statistical analysis of gold grades series

| Drift	Sample No	Mean(g/t)	Minimum(g/t)	Maximum(g/t)	Standard deviation	Kurtosis	Skewness	JB-statistic
−290 m	S1	1.01	0.1	4.5	0.82	1.68	1.21	4.67×10^1*
	S2	1	0.1	18.6	2.12	44.33	5.92	9.51×10^3*
	S3	2.33	0.1	20	2.89	8.48	2.4	7.34×10^2*
	S4	0.41	0.1	2.5	0.37	13.61	3.26	1.10×10^3*
	S5	1.05	0.2	15.3	1.64	6.69	1.56	1.44×10^4*
	S6	0.74	0.15	16.5	1.72	65.77	7.56	2.13×10^4*
−282 m	S7	1.82	0.1	12.3	1.64	10.21	2.24	7.76×10^2*
	S8	2.72	0.1	39.35	4.45	47.66	6.45	1.21×10^4*
	S9	2.11	0.1	13.3	2.32	5.75	2.03	3.07×10^2*
−210 m	S10	0.61	0.1	11.5	1.23	61.98	7.17	1.64×10^4
	S11	1	0.1	4.8	0.78	4.4	1.52	1.36×10^2*
	S12	1.35	0.1	9.7	1.46	9.33	2.6	6.51×10^2*

*Statistical significance at the 5 % level

Eqs. (1)–(6) with q ranging from −5 to 5 in increments of 0.5. In order to avoid the statistical error dependent on size s, we take s from 5 to int (N/5) and $m=2$. Figure 3 shows the fluctuations $F_q(s)$ as a function of s, after elimination of a number of second-order non-linear trends, for different representative values of q ($q=−5, −3, 0, 3, 5$) for three sample, S4, S8, S12, for one sample of each class. The generalized Hurst exponents $h(q)$ can be obtained by observing the slope of the log-log plot of $F_q(s)$ versus s. In the estimation of the singularity strength $\alpha(q)$, suppose that $\widehat{\alpha}(q−0.5)$, $\widehat{\alpha}(q)$, and $\widehat{\alpha}(q + 0.5)$ are three successive estimates of $\alpha(q)$, and $\widehat{\alpha}(q)$ is shown in $\widehat{\alpha}(q) = \tau(q + 0.5) −\tau(q−0.5)$. The results of multifractal analysis using MF-DFA method are listed in Table 2.

The multifractal spectrum provides an adequate characterization of the multifractal nature of gold grades series fluctuations and makes it possible to describe in detail. In Fig. 4, $\tau(q)$ and $f(\alpha)$ and they are concave functions of q, and the generalized Hurst exponent $h(q)$ are decreasing functions which exhibit a strong dependence on q (see Fig. 6, h_{orig}), which confirm the multifractal behavior of these series. The left- side of $f(\alpha)$ curve represents high value distribution whereas the right-side corresponds to that of low values. When high values are suppressed, the $f(\alpha)$ curves are called right-deviated multifractal (RM) in geology field. On the contrary, the $f(\alpha)$ curves have left-deviated multifractal (LM) if low values are truncated.

Table 2 shows that the $h(2)$ ranges between 0.5 and 1, and the series exhibits a long memory or persistence. The values of $h(2)$ are more than 0.68 in S3, S4, S6, S8, S9 and S10, which indicate that the low grades in barely mineralized drifts and
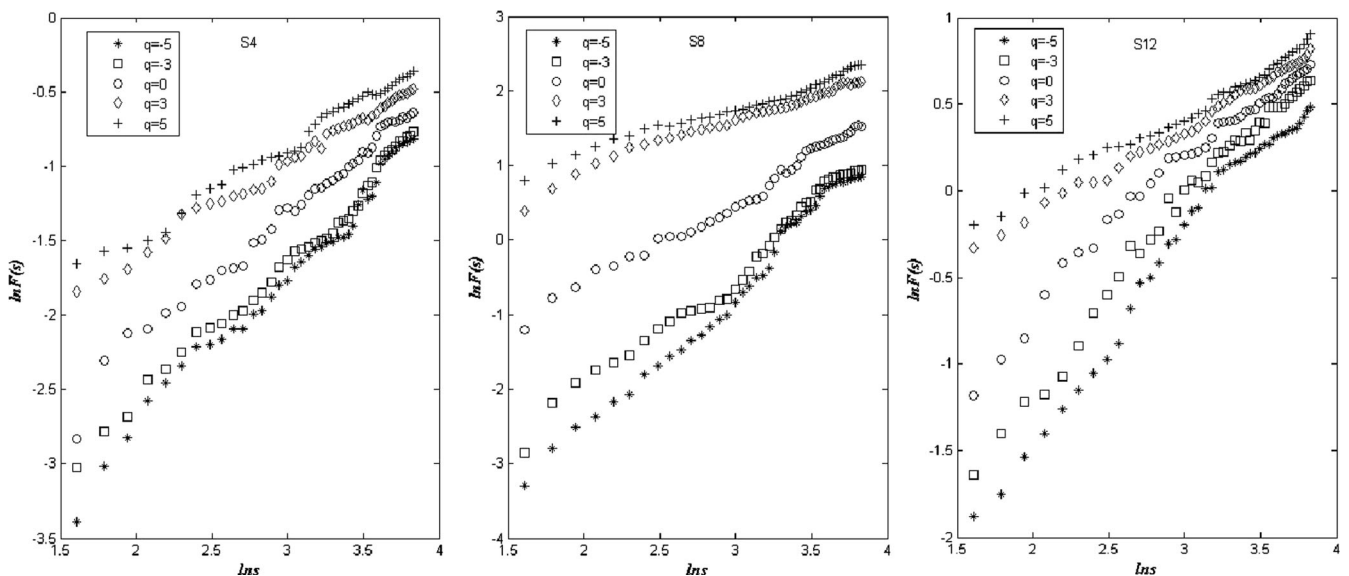
Fig. 3 the log-log plot of fluctuation function $F_q(s)$ versus s for various values of q: $q=−5$ (*star*), $q=−3$ (*squares*), $q=0$ (*circles*), $q=3$(*diamond*), and $q=5$(*cross*), S4, S8, S12

**Table 2** Multifractality parameters of the gold grades series

| Drift	Sample No.	rank	$h(2)$	$\Delta\alpha_L$	$\Delta\alpha_R$
−290 m	S1	II	0.57	0.25	0.85
	S2	II	0.58	0.81	1.43
	S3	III	0.68	0.55	1.12
	S4	I	0.68	0.47	0.26
	S5	II	0.5	0.76	0.39
	S6	I	0.70	1.22	0.12
−282 m	S7	II	0.52	0.89	0.86
	S8	III	0.71	0.85	1.13
	S9	III	0.89	0.42	0.54
−210 m	S10	I	0.71	1.36	1.1
	S11	II	0.53	0.36	0.39
	S12	II	0.57	0.37	0.43

the high grades in intensely mineralized drift have relatively strong the long-range correlation. The exponent $\Delta\alpha_L$ is less than $\Delta\alpha_R$ in S3, S8, S9 (intensely mineralized), which means that the geochemical field is RM type and high local enrichment. By contrast, the exponent $\Delta\alpha_L$ is greater than $\Delta\alpha_R$ in S4, S6, and S10 (barely mineralized drifts), which means that the geochemical field is LM type and local pauperization. The $h(2)$ of the other samples are around 0.5, indicating stronger random property in moderately mineralized drifts, and it is uncertain to make comparable results for the values of $\Delta\alpha_L$ and $\Delta\alpha_R$. In combination of the parameters of the result of multifractal, $h(2)$, $\Delta\alpha_L$ and $\Delta\alpha_R$, the mineralization intensity in drifts was identified.

We calculate both the autocorrelation function with time lags of 1–40 m (in Fig. 5), which it shows a continuous increase of spatial correlation towards the origin.

Furthermore, we are interested in the nature of the multifractal behavior of the gold grades series. Here, we would like to distinguish between these two types of multifractality. In general, two different types of multifractality in time series can be distinguished: (i) Multifractality due to a fatness of probability density function (PDF) of the time series. In this case the multifractality cannot be removed by shuffling the series. (ii) Multifractality due to different correlations in small and large scale fluctuations. In this case the data may have a PDF with finite moments. Thus the corresponding shuffled time series will exhibit monofractal scaling, since all long-range correlations are destroyed by the shuffling procedure. Hence, if the multifractality only corresponds to the long range correlation, we may find $h_{shuf}=0.5$, and where the source of multifractality is exclusively due to the width of the probability density function, both h_{orig} and h_{shuf} are of the same value. In order to quantify the influence of the fat-tail distribution, surrogate time series were generated from the original by randomizing their phases in the Fourier space. The multifractality nature due to the fat-tail of the PDF signals is not affected by the shuffling procedure. To determine the multifractality due to the broadness of PDF, surrogate series were generated from the original by randomizing their phases in the Fourier space. The correlations in the surrogate series do not change, but the probability function changes to the Gaussian distribution. If multifractality in the time series is due to a broad PDF, $h_{sur}(q)$ obtained by the surrogate method will be independent of q. If both kinds of multifractality are present, the shuffled and surrogate series will show weaker multifractality than the original one (Matia et al. 2003; Movahed et al. 2006).

The shuffled and surrogate series of original were obtained by Matlab 7.1. Each sample was generated 10 times in order to
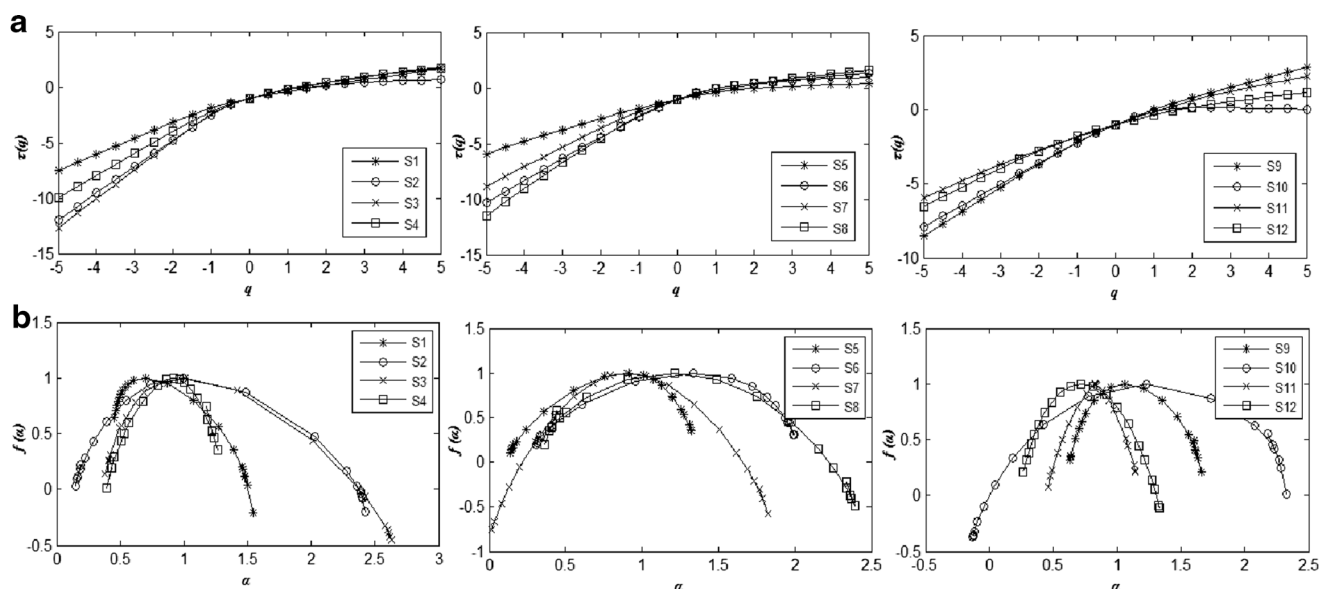
Fig. 4 Multifractality of gold grades series for $q=−5, −4, −3, …, 3, 4, 5$. **a** the scaling exponent $\tau(q)$, and **b** the multifractal spectrum $f(\alpha)$
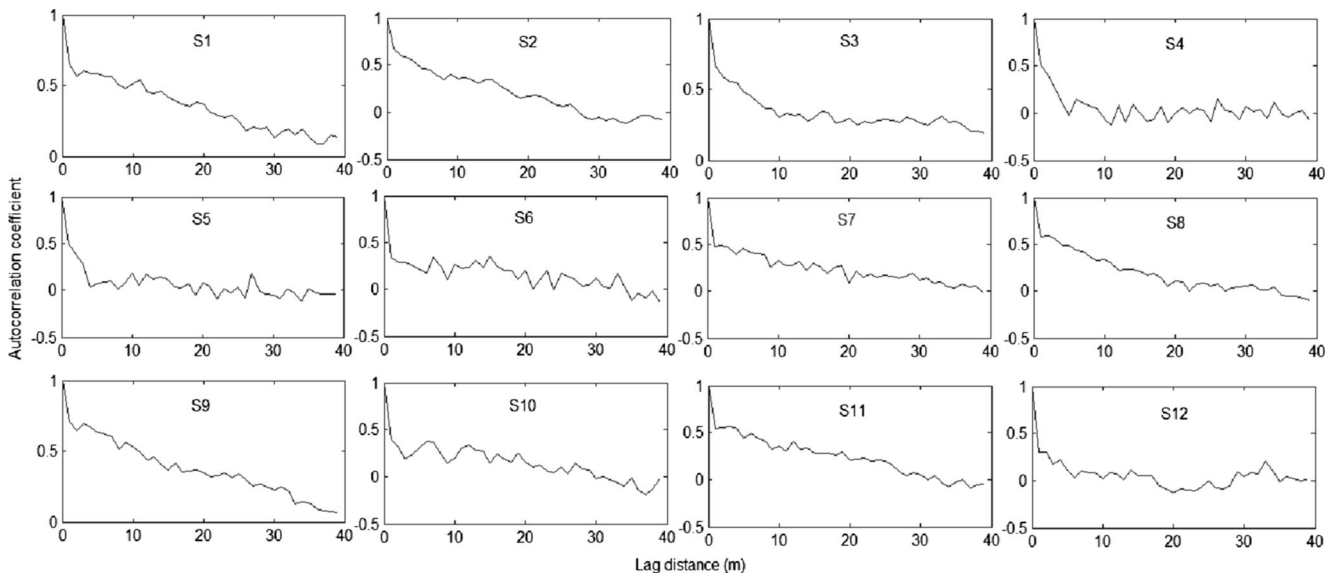
Fig. 5 Autocorrelation function of the gold grades from S1 to S12

reduce the statistical errors. The q-dependence of the exponent $h(q)$ for original(star), shuffled (circles) and surrogate(square) series via the MFDFA-2 are shown in Fig. 6. It should be noted that always $h(q)$ decreases with q. Thus, we can confirm the multifractal nature for all the cases. Multifractality degrees, Eq. (13), for the original, shuffled and surrogate series are reported in Table 3 for the gold grades. In the shuffled and surrogate cases the multifractality degree is estimated averaging of the ten realizations. Standard deviations are in parentheses. By contrast, in Fig. 6 the generalized Hurst exponent of original series h_{orig} and shuffled series h_{shuf} curves almost overlap in S5, a loss of multifractality in other cases is noted, and the source of multifractality due to the different long-range correlations of the small and large fluctuations has been

destroyed through the shuffling procedure, but the shuffled time series also show a multifractal nature. Moreover, the multifractality degrees of the surrogates are typically much narrower than for the reshuffled data, the $<\Delta h_{sur}>$ is smaller than $<\Delta h_{shuf}>$ in all samples, which can be interpreted as an evidence of the influence of extremely large non-Gaussian events on the fractal properties of the time series, which indicate that the multifractal structure of gold grades series in the Dayingezhuang gold deposit can be mainly attributed to the broad fat-tail distributions.

According to the results, series of gold grades are multifractal processes, as indicated by the strong q dependence of $h(q)$ and $\tau(q)$ in series of gold grades. This q-dependence has different behaviors for $q < 0$ and $q > 0$ in all these
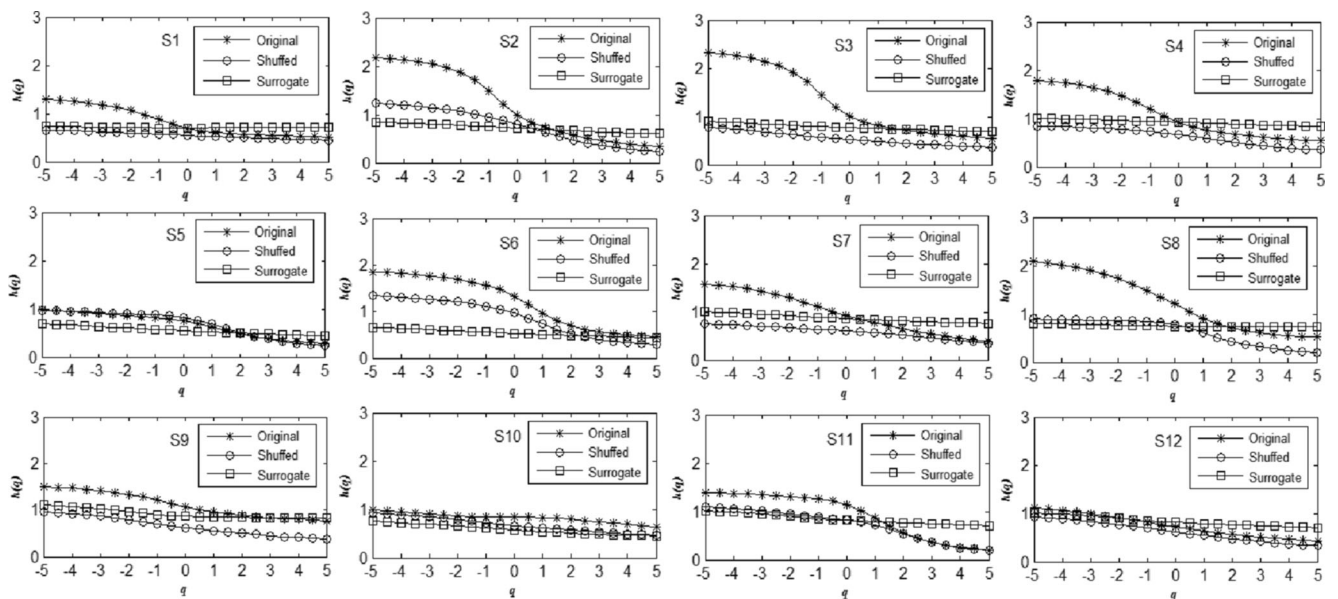
Fig. 6 Comparison of the generalized Hurst exponent $h(q)$ as a function of q for original, shuffled and surrogate series of gold grades from S1 to S12

Table 3 Degrees of multifractality for the gold grades series via the MFDFA-2

Drift	Sample No.	Δh_{orig}	$<\Delta h_{shuf}>$	$<\Delta h_{sur}>$
−290 m	S1	0.707	0.185(0.091)	0.004 (0.081)
	S2	1.754	0.944 (0.167)	0.216 (0.094)
	S3	1.659	0.349 (0.074)	0.176 (0.055)
	S4	1.149	0.468 (0.103)	0.147 (0.080)
	S5	0.650	0.648 (0.094)	0.207 (0.058)
	S6	1.328	1.006 (0.170)	0.183 (0.052)
−282 m	S7	1.092	0.365 (0.097)	0.202 (0.054)
	S8	1.442	0.671 (0.129)	0.048 (0.018)
	S9	0.676	0.521(0.171)	0.221(0.068)
−210 m	S10	0.284	0.399(0.114)	0.256(0.049)
	S11	1.155	0.839(0.101)	0.254(0.057)
	S12	0.601	0.519(0.096)	0.135(0.051)

studied series. Thus, it can be stated that the series of gold grades are of the multifractal nature. Hence, this study reveals that the series of gold grades exhibit a multifractal behavior, which can be characterized by using the MF-DFA. This finding allows us to use MF-DFA as a suitable tool for the description and characterization of gold grades fluctuations in drifts at different levels.

Conclusions

In the present paper we applied the multifractal detrended fluctuation analysis to investigate the multifractal behavior of the gold grades series in the Dayingezhuang gold deposit, Jiaodong province, China. The major conclusions are as follows:

1. According to the results of characteristics parameter, the gold grades series exhibit multifractal scaling, as indicated by the strong q dependence of $h(q)$ and $\tau(q)$.
2. By analyzing the Hurst exponent values $h(2)$, the low grades in barely mineralized drifts and the high grades in intensely mineralized drift have relatively strong long-range correlation. Hurst exponent values of moderately mineralized drifts are close to 0.5, indicating strong random property.
3. The asymmetry of multifractal spectrum shows that the range of the right-side branches of the multifractal spectrum is larger than that of the left-side branches for the gold grades series of intensely mineralized drifts, but the gold grades series of the barely mineralized zones are on the contrary. The shape of multifractal spectrum may provide directions in the study of ore-forming potential.
4. By comparing the multifractality of the original, shuffled and surrogate series to distinguish the two types of

multifractality, it is shown that all the samples exhibit the different degrees of multifractal scaling and long-range correlations, in which the multifractality degrees for the surrogates are typically much narrower than that for the reshuffled data. The multifractality structure of gold grades series may be mainly attributed to the fat-tail distributions and secondarily to the long-range correlations.

However, the potential of multifractal analysis is far from being fully exploited. How to deeply understand the essence of the multifratcal characteristics in metallogenic system and how to reveal more valuable information about metallogenic gold grades fluctuated are two key issues in the future. Study on these issues will help to make more accurate estimates for investigating the complexity of ore formation and potential forecast.

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