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Fractal analysis of geochemical landscapes using scaling noise model

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ABSTRACT

Fractal/multifractal concepts have facilitated the description and analysis of complex geochemical data in both mineral exploration and environmental studies. Scaling ($1/f^{\beta}$) noise has been ubiquitously found in geosciences but lack in-depth studies for geochemical distribution pattern in mineral exploration. In the present paper, the $1/f$ scaling natures of geochemical landscapes are investigated using spectral method through geochemical samples in stream sediments from Nanling Range, China. The results show explicit differences in scaling exponent (β) between major elements and trace elements, between highly enriched elements (e.g., W, Sn, Mo and Bi) and relatively low enriched elements (e.g., Au, Ag and Cu), where β measures the strength of persistence (or the degree of roughness) of geochemical landscapes. Furthermore, fractal mapping of geochemical patterns (W and Sn element) is undertaken to reveal the spatial association between local fractal dimension and mineralization. The finding is that most of the W and Sn deposits in study area exhibit rough geochemical patterns with fractal dimension ranging from 2.3 and 2.7 ($2.6 \le \beta \le 3.4$). We proposed to recognize the complex geochemical anomalies containing both stochastic (irregular) and deterministic (regular) components from fractal noise perspective.
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1. Introduction

Fractal geometry was introduced and popularized by Mandelbrot (1967, 1989) to describe complex natural objects showing similar geometries over a variety of scales. This fractal/scaling nature, resulting from the combination of regular (deterministic) and irregular (stochastic) factors, is commonly characterized with fractal dimension that is non-integer greater than or less than the integer Euclidian dimension. The past 40+ years have seen the extensions of fractal theory from geometries to fields that significantly increase its applicability. Fractality (self-affinity) generally follows power-law type relations associated with scale-invariance that can be represented as straight line on a log–log paper. The scale-invariant processes broadly exist in geosciences (Turcotte, 1997; Cheng, 2008), such as earthquakes, floods, hurricanes, volcanoes, rains and clouds. Recent studies suggest that mineralization in the crust could be considered as one type of scale-invariant geoprocess (Cheng, 2008), and ore deposits resulting from huge accumulation of metal elements often generate singular geochemical distribution which manifests fractal/multifractal natures.

Geochemical exploration have found with increasingly interests and benefits of using fractal (power-law) models to characterize geochemical distribution, including concentration–area (C–A) model (Cheng et al., 1994; Cheng, 2012), concentration–distance (C–D) model (Li et al., 2003), and concentration–volume (C–V) model (Afzal et al., 2011; Afzal et al., 2013), to name but a few examples. These fractal models are particularly useful for handling geochemical data including the separation and identification of geochemical anomalies, thereby assisting in mineral exploration (Cheng et al., 1994; Cheng, 2007). Local singularity analysis (LSA) is a well-known example of using density-area fractal model for weak information extraction by mapping the spatial distribution of local singularity strength (local fractal dimension) for complex geochemical landscapes (Cheng, 2008, 2012). Several case studies have demonstrated that the LSA or singularity mapping method is a powerful tool for discovering concealed ore deposits as well as other buried geological bodies (Cheng, 2006, 2007; Zuo et al., 2009; Agterberg, 2014a; Chen et al., 2015).

The scaling ($1/f$) noise/process has been widely found in the nature, depicting that the power density spectrum, $S(f)$, of self-affine time series scales as a power-law of the frequency ($1/f^{\beta}$). The spectral analysis is a commonly used method to study the $1/f$ scaling nature of geofields in the Fourier domain (see e.g., Huang and Turcotte, 1989; Malamud and Turcotte, 1999), and the scaling exponent (β) can measure the strength of persistence, namely, the correlations between adjacent values within the time or spatial series. Lovejoy and Schertzer (2007) reviewed specifically that geofields (e.g., topography, turbulence, rock density and susceptibility, magnetic and gravitational fields) possess scale-invariance over wide range of scales. For instance, spectral analysis of rock susceptibilities showed a wide range of β-*values* ranging from 1 to 5, which enlightened the understanding of the fractal nature of magnetic sources within the crust (Pilkington and Todoeschuck, 1993; Maus and Dimri, 1994; Lovejoy et al., 2001). Although the mechanism of $1/f$ scaling

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nature of magnetization distribution remains unclear, it indeed facilitated the interpretation of magnetic data such as the depth determination of magnetic sources (Bouligand et al., 2009; Bansal and Dimri, 2014).

Based on multifractal theory, Cheng et al. (2000) have developed a spectrum–area (S–A) model to quantify the anisotropic scaling properties of geochemical and geophysical fields, which depict a generalized power-law relation between power spectrum and area of power spectrum exceeding a threshold. According to the S–A model, the isotropic $1/f$ scaling behavior in the frequency domain becomes a special case in which the scaling exponent can quantify some types of spatial association indexes (persistence, correlation, and roughness). In applied geochemistry, conventionally, the spatial variation (e.g., spatial correlation and variability within agent area) is quantified by autocorrelation and semivariogram, which has been widely taken into account in the spatial statistical methods for handling geochemical data (Cheng, 1999b; Agterberg, 2012a), such as moving average, kriging and spatial factor analysis. Accordingly, the scaling exponent (or fractal dimension) obtained from spectral method could provide an alternative approach to evaluate the spatial variation and quantify the scale invariance of geochemical variables from a fractal perspective.

To date, research intentions have not been given enough to explore the $1/f$ scaling natures of geochemical landscapes. This study is devoted to use scaling noise to model geochemical landscapes and to investigate the implication of scaling exponent (β) especially for geochemical anomalies associated with mineralization. We describe first the spectral method used to estimate the scaling exponent and fractal dimension of geochemical landscapes, then simulate fractal geochemical pattern aiming at understanding its scaling properties from fractal filtering point of view. Subsequently, a case study from the Nanling Range (China), which is endowed with abundant W–Sn mineral resources, help look at the diversity of $1/f$ scaling natures of real geochemical data, with a final intention to discuss the spatial association between fractal dimension and mineralization.

2. Methods

2.1. Fractal analysis

There exist several approaches to estimate the fractal dimension (D) for self-affine series (Cheng, 1999b; Malamud and Turcotte, 1999),

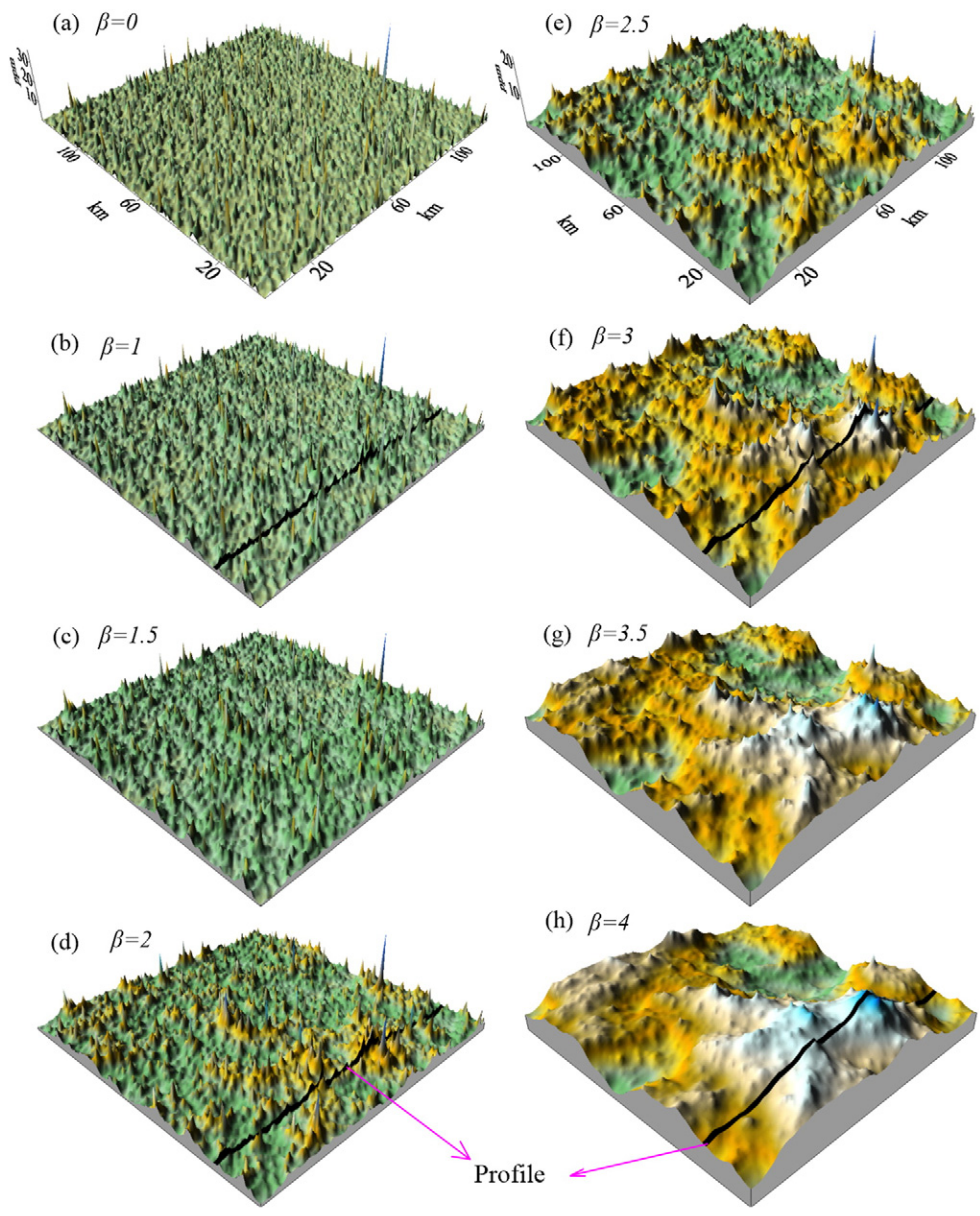

Fig. 1. Simulated fractal geochemical landscapes by using scaling filtering with different β-*values*: (a) 0, (b) 1, (c) 1.5,(d) 2, (e) 2.5, (f) 3, (g) 3.5 and (h) 4.

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