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Fault trace-oriented singularity mapping technique to characterize anisotropic geochemical signatures in Gejiu mineral district, China

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ABSTRACT

Mineralization is complex and controlled by various non-linear geo-processes. Geochemical signatures of mineralization-favored spaces inherited from multiple geo-processes are consequently anisotropic. Singularity index mapping technique efficient in identifying heterogeneity of geochemical signatures had been utilized to recognize geochemical anomalies in many cases. As an example of interdisciplinary collaboration, this paper using a newly proposed fault trace-oriented singularity index mapping technique intends to characterize hydrothermal mineralization-associated anisotropic geochemical signatures. In the case study, fault traces in the Gejiu mineral district, China are divided into segments with equal length. Centered by fault segments, a set of rectangular windows are defined to estimate singularity index. Variations of geochemical signatures along the vertical direction of fault traces are characterized. The fault trace-oriented singularity indices assigned to their corresponding fault segments term faults as positive, negative and regular fault segments to qualitatively and quantitatively explain interrelations between fault structures and hydrothermal fluids or mineralization. In comparison with frequently employed fault properties (e.g., length, density, types, etc.), the new fault attributes (i.e., positive, negative, and regular fault segment) are applicable to describe variations of physical–chemical reactions between ore-forming fluids and wall rocks along fault traces that benefit the interpretation to metallogenic mechanism. The newly proposed method can be considered as a supplement to the formerly introduced square window-based isotropic singularity index mapping technique.

1. Introduction

Mineralization is a complex and non-linear dynamic process (Cheng, 2007; Cheng and Agterberg, 2009; Yu, 2002; Zhao, 1999). As an end product of mineralization, formation of mineral deposits is caused by multiple geo-processes consisting of ore-forming element activation/transportation, ore-bearing fluid formation, migration, accumulation and precipitation, etc. Furthermore, these geo-processes are associated with many issues respectively. Interactions between fluids and tectonism believed as important ones mostly influence mineralization, and concerns to these two are thus significant to mineral exploration (McCaffrey et al., 1999). Fluid as a major medium to extract and transport ore-forming materials from their original positions can facilitate dispersion and accumulation of ore-forming materials (Zhai et al., 1999). Meanwhile, tectonism within the metallogenetic environment plays an important role in influencing the physical and chemical properties of ore-forming fluids (McCaffrey et al., 1999; Zhai et al., 1999). First of all, the prominent decrease of tectonic stress within the faults (e.g., the dilatant faults) can benefit alteration of the thermodynamic equilibrium among various components of fluids when they are passing through the fault system. Consequent variations in component concentration and saturation which further disturb the physical–chemical stability of fluids may cause the occurrences of mineralization. Secondly, the variation of tectonic stress can cause dissolution, activation and migration of ore-forming materials from ore-bearing strata to hydrothermal fluids. Dilatant structures with high permeability can advantage the dispersion of ore-forming materials and provide space for mineralization. In addition, connectivity between fault systems is another important factor in the formation of mineral deposits (i.e. Roberts et al., 1998, 1999). Therefore, proper analysis for tectonic systems will benefit understandings of mineralization, especially hydrothermal mineralization.

Hydrothermal mineralization is an important mineralization type in geosciences, the occurrence of which is normally dominated by three controlling factors consisting of igneous intrusions, mineralization-favored wall rocks and tectonic systems, (Cheng, 2007; Heinrich, 1995; Wang et al., 2011, 2012; Zhao et al., 2012). The previous two factors determine chemical reactions during mineralization, which confine the occurrences of metasomatism within the mineralization system

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(Yuan et al., 1979). Controlling effects of tectonic systems on spatial and mechanical characteristics of hydrothermal deposits are undertaken by two properties: tectonic scales and stages (Zhai et al., 1999). In general, local tectonics influence the local distribution, shapes and interior structures of hydrothermal ore bodies, while regional tectonics influence the spatial distribution and properties of hydrothermal deposits (Faulkner et al., 2010; Micklethwaite et al., 2010; Zhai et al., 1999). Chronologically, tectonic stages involve pre-, syn- and post-mineralization tectonics which provide spaces for ore-bearing fluid flow, release pressure in wall rocks and affect deposits mechanically (e.g., re-shaped, disassemble or supergene enrichment), respectively (Zhai et al., 1999). Since the effects of tectonic system on hydrothermal fluid flow and ore formation, properties of tectonic activities (e.g., types and spatial distributions) have long been noticed. Fault as one of the most significant productions of tectonic activities is the focus of many researches (Faulkner et al., 2010; Kim and Sanderson, 2005; Torabi and Berg, 2011). By analyzing fault properties (e.g., fault length, population, and displacement, etc.), knowledge regarding to various mineralization-associated issues can be derived to support further studies (Agterberg et al., 1996; Wang et al., 2012; Zhao et al., 2011).

It is broadly understood that the formation of faults and geochemical haloes is caused by multiple non-linear geo-processes, the distributions of which are consequently complex and anisotropic (Agterberg, 2012; Agterberg et al., 1996; Cheng, 2007; Zhao et al., 2011). As the description in Zhai (2003), migration of geochemical elements cannot occur without force and power. Forced by tectonic stress, geochemical elements are transported within the spaces of faults toward certain positions and further mineralized accompanying with heterogeneously distributed geochemical anomalies, rock deformation and/or metamorphism of wall rocks. As a result, the geochemical anomalies are spatially confined within certain tectonic units, and faults can be accordingly identified by the long axis of anomalous patterns in some cases (Zhai et al., 1999). The tectonic stress-related deformation and geochemical element accumulation constitute a uniform physical–chemical system, so-called as tectonic–geochemical system (Zhai et al., 1999). Therefore, concerns of interrelations between geochemical signatures and tectonic features are necessary to understand the tectonic–geochemical associated mineralization. Interpretation of the interrelations requires the collaboration of geochemistry and tectonics in many cases.

With the development of computer sciences (De Paor, 1996) and constructions of geo-database all over the world (Darnley, 1995), multidisciplinary approaches nowadays are flourishing. Geosciences as the beneficiary have been greatly progressed in geo-information integration for datasets from multi-source and at multi-scale (Cheng, 2012; Harris et al., 1998; Wang et al., 2011). Among these interdisciplinary collaborations, tectonic–geochemical exploration is the one employed frequently (Wang et al., 2012; Zhai, 2003; Zhai et al., 1999). Statistical methods are popular and effective to frequency domain rather than spatial domain, by which optimal buffers of fault traces and their intersections are often applied as indicators to mineralization-favored spaces (Bonham-Carter, 1994; Cheng et al., 2009b; Koch and Link, 1980). Since the concept of ‘fractals’ proposed by Mandelbrot (1983), fractal and multifractal approaches taking care of both frequency and spatial properties of geological signatures have been widely used to fault analysis (Agterberg et al., 1996; McCaffrey et al., 1999; Wang et al., 2012; Zhao et al., 2011). There is an increasing interest in applying fractal dimension and multifractal spectra to describe complexity and self-similarity of fault systems (Arias et al., 2011; Gumiel et al., 2010; Sanderson et al., 2008). In fractal/multifractal point of view, active and complex fault system corresponding with high fractal dimension can benefit ore-bearing fluid flow and provide favorable environment for mineralization (Zhao et al., 2011). Furthermore, the multifractal based singularity index mapping technique (Cheng, 2007) has proven to be efficient in qualitatively and quantitatively characterizing spatial variations of fault density and delineating mineralization-favored spaces provided by fault systems (Wang et al., 2012).

After characterizing spatial distribution of fault intensity and modeling hydrothermal mineralization-associated tectonic–geochemical signatures in southeastern Yunnan mineral district, China by Wang et al. (2012), this study as a successor to the previous research intends to apply an interdisciplinary collaboration method to characterize anisotropic distributions of geochemical signatures in this area. In addition, current results will define a new fault property based on variations of geochemical signatures or mineralization favorability along the directions of fault traces which may be of great interest to prospectivity.

2. Singularity index mapping techniques

In this paper, the singularity index mapping technique by a square window-based method is reviewed, which is to characterize isotropic properties of geological features related to hydrothermal mineralization. As an improvement, a new fault trace-oriented singularity index mapping method is currently proposed to delineate anisotropic properties of geochemical anomalies associated with mineralization.

2.1. A square window-based singularity index mapping technique

Proposed by Cheng (1999), singularity is a multifractal concept to characterize geo-processes accompanying with energy release and material accumulation within small spatial–temporal intervals. By a square window-based singularity index mapping technique, anomalous concentrations of elements caused by both hydrothermal mineralization (Cheng, 2007; Cheng and Agterberg, 2009) and magmatism (Zhao et al., 2012) and variations in geophysical fields by different causative geologic bodies (Wang et al., 2011, 2013) can be characterized in space. In addition, it helps to deal with other environmental issues as well, such as changes in runoff by peak flow events (Cheng et al., 2009a). Zuo et al. (2009, 2013) stated that the singularity index mapping technique is efficient in indicating weak geo-anomalies usually hidden within a strong variance of background (Arias et al., 2012; Zuo and Cheng, 2008). More details and applications of singularity theory can be found in Cheng (2000, 2006) and Agterberg (2012).

Within the circumstance of hydrothermal mineralization, the amount of metals in an area A can be denoted as $\mu(A)$ and the concentration of the metals within A is $C(A)$ (Cheng, 2007). As described in the Introduction, mineralization-associated geochemical distributions are heterogeneous. The changes of A will influence values of both $\mu(A)$ and $C(A)$. Therefore, caused by the non-linear hydrothermal mineralization process, $\mu(A)$ and $C(A)$ follow a power-law relationship with A in a 2-D scenario, respectively.

$$\langle \mu(A) \rangle = cA^{\alpha/2} \tag{1}$$

$$\langle C(A) \rangle = cA^{\alpha/2-1} \tag{2}$$

where, c is a constant determining the magnitude of the function, and α, or so-called singularity index is a scaling exponent of the power-law relationship preserving the shape of the function and the changes in metal mass and/or concentration across the spaces. The power-law relationship is represented in a statistical sense as <> or “expectation”.

By the square window-based mapping technique (Cheng, 1999), if a log-transformation is taken on both sides of Eq. (2), a linear relationship between $\log(\varepsilon_i)$ and $\log C[A(\varepsilon_i)]$ can be expressed as:

$$\log C[A(\varepsilon_i)] = c + (\alpha - 2)\log(\varepsilon_i) \tag{3}$$

where, $A(\varepsilon_i) = \varepsilon_i \times \varepsilon_i$ represents areas of a set of predefined square windows with sizes ε_i ($\varepsilon_i = \varepsilon_1 < \varepsilon_2 < \varepsilon_3 \ldots < \varepsilon_n$) at locations i, and $C[A(\varepsilon_i)]$ is the average metal concentration within areas $A(\varepsilon_i)$. Plotting each pair of log-transformed ε_i and $C[A(\varepsilon_i)]$ in Cartesian coordinate system, a linear trend can be achieved by the least-squares method (Fig. 1). The slope of Eq. (3) defined by $(\alpha - 2)$ is used to estimate the