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Delineation of supergene enrichment, hypogene and oxidation zones utilizing staged factor analysis and fractal modeling in Takht-e-Gonbad porphyry deposit, SE Iran

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ABSTRACT

The aim of this study is to delineate the different mineralized zones consisting of supergene enrichment hypogene and oxidation zones in Takht-e-Gonbad porphyry Cu deposit (SE Iran), subsurface data and using the staged factor analysis (SFA) and concentration–volume (C–V) fractal modeling. Results obtained by SFA reveal that Cu and Mo were situated in a factor as F1–5 which was modeled by C–V fractal modeling for separation of the mineralized zones. The supergene enrichment zone obtained by the SFA and C–V fractal modeling contains 1.16% for Cu and 241 ppm for Mo. Moreover, the hypogene zone derived via the SFA and C–V fractal modeling has Cu and Mo mean values of 0.65% and 109 ppm. These mineralized zones were correlated with geological models utilizing logratio matrix which indicate that the obtained zones based on the SFA and C–V fractal model are consistent with the geological models. The results derived via logratio matrix reveal overlapping between geological and mathematical models. As a result, combination of the C–V fractal modeling and SFA can be used to delineate mineralized zones based on multivariate data.

1. Introduction

Since 1904, porphyry copper deposits have represented the main resource/reserve of copper all around the world. This type of deposits is the most important with respect to high tonnage of ore values for Cu, Mo, Au and Sn. One of the essential studies on the porphyry deposits is identifying mineralized zones particularly supergene enrichment and hypogene zones (Robb, 2005; Berger et al., 2008; Pirajno, 2009). Conventional geological methods for detection and recognition of supergene enrichment and hypogene zones in the porphyry deposits are based on mineralographical and petrographical studies (e.g., Lowell and Guilbert, 1970; Cox and Singer, 1986; Berger et al., 2008). However, statistical analysis and mathematical methods have been utilized to distinguish mineralized zones since the 1950s (e.g., David, 1970; Davis, 2002). The main aim of statistical analysis, particularly factor analysis, is to extract a few ‘factors’ to raise the ability of illustrating multivariate data (Treiblmaier and Filzmoser, 2010; Yousefi et al., 2012, 2014). Staged factor analysis is one of multivariate statistical techniques which can reduce variables (elements) and define paragenetic elements in different factors (Yousefi et al., 2014).

Fractal/multifractal modeling has been widely used in the mineral exploration and economic geology specifically for the identification of geochemical anomalies and mineralized zones (e.g., Cheng et al., 1994; Agterberg, 1995; Li et al., 2003; Zuo et al., 2009; Afzal et al., 2011; Hassanpour and Afzal, 2013; Rahmati et al., 2014). Several fractal models have been developed and proposed in geochemical exploration to separate geochemical populations, e.g., concentration–area (C–A: Cheng et al., 1994), concentration–distance (C–D: Li et al., 2003), number–size (N–S: Mandelbrot, 1983) and its 3D form by Sadeghi et al. (2012), simulated size–number (SS–N: Sadeghi et al., 2015) and concentration–volume (C–V: Afzal et al., 2011) based on surface and subsurface data. In this paper, the staged factor analysis is used for reducing factor and defining paragenesis factor for Cu and Mo and utilized the C–V multifractal model for separating various mineralized zones in Takht-e-Gonbad porphyry deposit, SE Iran, and the results are correlated with the geological modeling.

2. Methodology

2.1. Staged factor analysis

Multivariate statistical methods such as factor analysis supposes that data have normal (symmetric) distribution; however, geochemical exploration data never demonstrate a normal distribution (Reimann and

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Filzmoser, 2000; Yousefi et al., 2012; Yousefi and Carranza, 2015a). The major purpose of the factor analysis is to realize a few and common factors from multivariate data (Treiblmaier and Filzmoser, 2010; Yousefi et al., 2012; Yousefi and Carranza, 2015b). The accuracy of the factor value measurements changes with element concentration; these values are less accurate at very low and high concentrations (Reimann and Filzmoser, 2000). The geochemical data distribution are not symmetric and most of geochemical data are compositional data (Filzmoser et al., 2009; Yousefi et al., 2012; Yousefi and Carranza, 2015c) which means that they system in which individual variable are not independent of each other (Carranza, 2011). Therefore, normalization operation must be applied to these data. In this paper, the natural logarithm (Ln) was used for transforming values of multivariate geochemical data in a classical factor analysis by SPSS v. 23 software. After transformation of geochemical data, standard techniques such as classical estimation of correlation matrix were used to find the relation between all the variables. More over principal component analysis (PCA) is utilized to extract principal components for identifying hidden multivariate data structures and decreasing the number of variables (Filzmoser et al., 2009; Yousefi et al., 2012; Gholami et al., 2012). The staged factor analysis consists of two main phases as follows:

The first phase is for extraction of 'clean' factors and the second phase is for extraction of a significant multi-element zonation signature of the mineral deposit-type sought to calculate reliable loadings and factor scores. On the other hand, elements are not situated in any factors should be rejected for generating clean factors. Each of the main phases of the staged factor analysis may comprise sub-phases depending on geochemical data and the mineral deposit-type sought (Yousefi et al., 2014).

In this paper, five stages of factor analysis were carried out to achieve main multi-element anomalous geochemical data of Takht-e-Gonbad deposit. These elements are Cu, Mo and Ag and the final stage was named F1–5. This Stage was used in the C–V fractal modeling for identifying zones.

2.2. Concentration–volume (C–V) fractal modeling

Afzal et al. (2011) proposed the C–V fractal model for delineation of mineralized zones and barren host rocks in different ore deposits, especially in porphyry Cu deposits, this model can be expressed as:

$$V(\rho \le \nu) \propto \rho^{-a1};\, V(\rho > \nu) \propto \rho^{-a2} \qquad (1)$$

where V ($\rho \le \nu$) and V ($\rho > \nu$) indicate volumes (V) with concentration values (ρ) smaller and greater than contour values (ν), respectively, a1 and a2 are characteristic exponents.

Different mineralized zones in the ore deposits (Cu porphyry deposit in this scenario) have fractal properties and are defined by power law relationships between their ore element concentrations and volumetric extensions. Represented breakpoints in C–V log–log plots of concentration values versus volumes separate geochemical populations by threshold values. Breakpoints in the log–log plots outlined various populations of geochemical concentration values representing different lithological and mineralogical zonation.

3. Geological setting of the study area

3.1. Regional geology

The Takht-e-Gonbad porphyry Cu deposit is situated about 70 km NE of the Sirjan city, SE Iran. Most of the Cu porphyry deposits of Iran occurred in the Cenozoic Urumieh–Dokhtar magmatic belt which is one of the subdivisions of the Zagros orogenies (Alavi, 1994; Dargahi et al., 2010; Asadi et al., 2014). These are particularly revealed in the SE arc segment which is referred to Kerman Cenozoic magmatic arc (KCMA) with 450 km length and 60–80 km width (Fig. 1: Shafiei et al., 2009; Asadi et al., 2014). The KCMA is situated on the western boundary of the Central Iranian block with calc-alkaline intrusive rocks (stocks) association (Asadi et al., 2014).

The Takht-e-Gonbad deposit is located on the center and south of KCMA as (Fig. 1).The initial exploration was started in the 1970s by Yugoslavian geologists and the result was impregnation tuffs as host rocks (Geological Survey of Iran, 1973). Based on the geological map of Takht-e-Gonbad deposit, Eocene volcanic–pyroclastic rocks and Neogene sediments such as carbonate units are the main rocks in the deposit (Fig. 1). Phyllic, argillic, propylitic, silicic and carbonate alteration zones were resulted in the Miocene granodiorite intrude to Eocene volcanic–pyroclastic rocks. Phyllic alteration is the main alteration type and is accompanied by hypogene zone in the Takht-e-Gonbad deposit. The region surrounding the deposit is tectonically active and most of the faults occurring in this deposit are affected by Nain–Baft fault (Hosseini, 2012: Fig. 1).

3.2. Mineralization and alteration

Mineralization in the KCMA occurred in quartz stockworks, veins and as spread sulfides in both the host stock and surrounding the older volcanic and pyroclastic rocks (e.g., Shafiei et al., 2009; Asadi et al., 2014). At Takht-e-Gonbad deposit, oxide, hypogene and immature supergene zones have been developed. The supergene enriched zone is distinguished mainly by chalcocite and covellite. This zone varies in thickness from 10 to 50 m (Hosseini et al., 2011; Hosseini, 2012).

Hypogene ore at Takht-e-Gonbad consists of pyrite, chalcopyrite and minor magnetite and molybdenite. The hypogene ore of economic grade has been traced for about 150 m below the oxide ore (Hosseini, 2012: Table 1). One of the important features of the deposit area is the N–S fracturing system which appears as late barren dykes and breccia pipes (Taghipour et al., 2008; Hosseini et al., 2011; Asadi et al., 2014). Hydrothermal alteration at Takht-e-Gonbad was distinguished by an extensive phyllic assemblage and irregular zones of propylitic and calc-silicate assemblages. Copper mineralization in the deposit is associated mainly with phyllic alteration zone. Maximum Cu grade is higher than 5%, however, it is rare, based on the logging and analysis of the drill cores.

4. Discussion

In this study, 39 drilled boreholes data including collar coordinates, azimuth, orientation (dip), lithology, alteration and mineralogy were used to create the 3D geological modeling, and also, the zonation, alteration, lithology and mineralization models were generated by RockWorks™ v.15 software package (Fig. 2). Based on the geological modeling, phyllic alteration zone, the granodiorite rocks and hypogene zone are expanded in the area and chalcopyrite is the major ore element in the deposit. From the drilled boreholes, 2830 lithogeochemical samples were collected and analyzed by ICP-AES for Cu, Mo, Ag, Cd, Co, Cr, Fe, Mo, Ni, Sb, Mn and Zn. Distribution of Cu and Mo were not normal. Therefore, natural logarithm transformer was applied to transform data distribution to symmetric the F-1–5 in the geostatistical and fractal modeling. The experimental semi-variogram for F1–5 data in the Takht-e-Gonbad deposit is demonstrate a range, nugget effect and spatial variance of 81 m, 0.418 and 0.536 %, respectively built up by Datamine Studio software (Fig. 3).

4.1. Application of staged factor analysis

In factor analysis, a threshold value for minimum loading criterion for elemental variables should be selected between the ranges of 0.3 to 0.6 in order to reduce the errors of the calculation of the scores (Fabrigar et al., 1999; Davis, 2002; Filzmoser et al., 2009). Consequently, the absolute value of 0.5 will be a medium loading value (Treiblmaier and filzmoser, 2010; Yousefi et al., 2012, 2014). In this study, 0.6 was selected for the minimum loading criterion. The classical principal factor