The aim of this research was the application of power spectrum-area (P-A) fractal model to separate geochemical anomalies for Cu, Mo and Au as a case study for Kahang porphyry Cu-Mo deposit, central Iran. Scaling distinctions (scaling range and power-law exponent) can be detected from the power spectrum field (S) by applying a $A(\geq S) \propto S^{-2/\beta}$ (Spectrum – Area) multifractal model. Multiple scaling properties (bi-fractal properties as a special case) were observed from lithogeochemical data from Kahang porphyry deposit, Central Iran. The power spectrum in the range of $S < 100$ reflects the elemental background in Cu-Mo porphyry mineralization and the exponent $2/\beta \geq 2$ indicates high intensity anomalies of those elements, whereas the depicted anomalies were correlated with geological including lithological units, alterations and faults. High intensity of elemental anomalies is located in central parts of the deposit and lower anomalies are situated in eastern and western parts.

Keywords: Power Spectrum-Area fractal model, Cu-Mo porphyry, Kahang, Multifractal

Celem badań było zastosowanie modelu fraktalnego moc widma – pole (P-A) w celu oddzielenia anomalii geochemicznych dla Cu, Mo i Au jako studium przypadku systemu Cu-Mo w porfirze z Kahang w środkowym Iranie. Parametry skalowania (zasięg skalowania i wykładnik prawa potęgowego) mogą być określone z pola widma mocy (S) poprzez zastosowanie wielofraktalnego modelu $A(\geq S) \propto S^{-2/\beta}$ (widmo-pole). Wiele właściwości skalowania (szczególnie przypadek bi-fraktalnych właściwości) zaobserwowano dla danych litogeochemicznych porfiru z Kahang. Widmo mocy w zakresie $S < 100$ odzwierciedla elementarne tło Cu-Mo mineralizacji w porfirze a wykładnik $2/\beta \geq 2$ wskazuje na wysoką intensywność anomalii tych elementów. Opisane anomalie były skorelowane z geologicznymi, takimi jak jednostki litologiczne,
1. Introduction

Separating signals into components and reducing the noise to signal ratio commonly involves the process of pattern recognition. Geochemical determinations of total or bulk concentration of elements in soils, humus, tills and rocks are commonly used in geological studies for detecting the influences of particular geological processes such as mineralization (Agterberg et al., 1996; Goncalves et al., 2001; Li et al., 2003). Decomposing bulk values into component patterns to reflecting the specific geological features is often essential part of prediction of mineral resources and exploration (Cheng & Li, 2002; Cheng, 2006). A number of parameters have been used in the past for pattern recognition. These include the magnitude of patterns, frequency distributions, geometry and texture. More recently, scaling properties have been recognized and incorporated in the pattern recognition (Cheng et al., 1994; Cheng et al., 1999; Panahi et al., 2004; Cheng, 2006; Ali et al., 2007). Scaling refers to the property that change of measuring unit does not alter the function type between measure and measuring unit. The governing function for scaling is the power-law function, \( \mu(\varepsilon) \propto \varepsilon^\alpha \), where \( \mu(\varepsilon) \) is a measure performed at scale \( \varepsilon \), \( \propto \) stands for “proportional to” and \( \alpha \) is the power-law exponent (Cheng et al., 1994; Cheng, 2006). Homogeneity scaling needs only a one-dimensional function with a unique exponent; otherwise, for generalized scale invariance, additional functions are needed to characterize the directional and rotational scaling properties. Physical processes over different scaling ranges result in the mixing of different components. Consequently, multiple scaling properties may be anticipated in modeling such measures. This paper introduces a recently developed method for decomposing geochemical patterns on the basis of scaling breaks detected from the power spectrum field. A case study of lithogeochemical data (Cu, Mo and Au) serves to demonstrate how the method can be used to separate geochemical anomalies from background related to Cu-Mo porphyry deposit in Kahang, central Iran.

2. Multifractal scaling

Fractal scaling of a measure (fractal or multifractal) usually involves both the range of scale (\( \varepsilon \)) over which the measure holds the scale invariant property and the actual scaling governing power-law itself, \( \mu(\varepsilon) \propto \varepsilon^\alpha \). The scaling range may be limited due to either the nature of the relevant physical process or the resolution and quality of the observed data (Cheng, 2006). Therefore, while it is important to utilize the power-law exponent to characterize the scaling properties of the measure, the scaling range itself plays an important role for differentiating between superimposed fractals or multifractal measures with different scaling properties. There have been many examples of fractal quantities showing bi-fractal properties (texture and structure dimensions). Most of the bi-fractal examples documented in the literature are defined in a space domain with a geometric measuring scale. A new power-law model was developed from a multifractal point of view by Cheng (2006) to characterize the scaling property of the power-spectrum in the fre-
quency domain. It involves power-law relations, \( A(\geq S) \propto S^{-2/\beta} \), between the power spectrum values \( S = ||F(W_x, W_y)|| \) and the “area” of the set with power spectrum values above \( S \), \( \{W_x, W_y : \geq S\} \), where \( F \) denotes a fast Fourier transformation of the measure \( \mu(x, y) \); \( W_x \), and \( Wy \) represent wave numbers in horizontal and vertical directions, respectively. The range of the exponent is \( 0 < \beta \leq 2 \) or \( 1 \leq 2/\beta \) with the special case of \( \beta = 2 \) or \( 2/\beta = 1 \) corresponding to non-fractal or monofractal measure \( \mu \), and \( 1 < 2/\beta \) to multifractals (details in Cheng, 2006). This model holds true for both isotropic measures and others with generalized scale invariance. Most of patterns which are extracted from exploratory geochemical and geophysical data can be considered as mixture of multiple components according to several processes. It may be anticipated that the power-law relationship \( A(\geq S) \propto S^{-2/\beta} \) to show a multi-scaling property over multiple scale ranges. The scaling breaks bounding the multiple ranges of power spectra can be identified on log-log plots of \( A(\geq S) \) vs. \( S \). Each such scale range then can be used to build define a frequency filter. Taking two filters for example, and assuming two ranges of power spectrum can be identified by fitting two different power-law relationships with exponents \( \beta_1 \) and \( \beta_2 \), respectively, then the threshold \( S_0 \) obtained from those two power-law relations can be used to form the two sets \( \{W_x, W_y : S \leq S_0, \beta_1\} \) and \( \{W_x, W_y : S_0 < S, \beta_2\} \), which can be further used to define two filters \( G_1(W_x, W_y) = 1 \) if \( W_x, W_y \in \{W_x, W_y : S \leq E_0, \beta_1\} \) and otherwise \( G_1(W_x, W_y) = 0 \). The other filter can be \( G_2(W_x, W_y) = 1 - G_1(W_x, W_y) \). Inverse fast Fourier transformation (iff) can be applied with these filters to move the decomposed components back to the space domain: \( \mu_1(x, y) = (F G_1)^{-1} \) and \( \mu_2(x, y) = (F G_2)^{-1} \). \( \mu_1(x, y) \) and \( \mu_2(x, y) \) are the decomposed patterns of \( \mu(x, y) \). In this special case where \( G_1 + G_2 = 1 \), then, \( \mu_1(x, y) + \mu_2(x, y) = \mu(x, y) \). In the more general case that a small range of power spectrum corresponding to a noise component is removed during the definition of the filters, the sum of the decomposed components will be slightly different from the original patterns. The decomposed components, \( \mu_1(x, y) \) and \( \mu_2(x, y) \), can be nonfractal, fractal, or multifractal quantities with less variability in comparison with the bulk measure \( \mu(x, y) \).

3. Geological setting of Kahang porphyry deposit

The Kahang area is located in about 73 km NE of Isfahan in Central Iran. Kahang porphyry deposit occurred in the Cenozoic Urumieh-Dokhtar magmatic belt, one of the subdivision of Zagros orogenies (Alavi, 1994). This belt extends from NW to SE Iran. All of the Iranian large porphyry copper deposits and systems such as Sarcheshmeh, Sungun, Meiduk and Darehzar are this belt (Shahabpour, 1994). Geological, geophysical, geochemical and alteration patterns show that there is a Cu-Mo porphyry system (Tabatabaei and Asadi Haroni, 2006).

The porphyry deposit is mainly composed of Eocene volcano-pyroclastic rocks, intruded by quartz monzonite, monzodiorite to dioritic intrusions in Oligo-Miocene rocks, depicted in Fig. 1. The extrusive rocks, including tuffs, breccias and lavas are dacitic to andesitic in composition. Magmatic events in Kahang area can be defined as follow:

1 – Explosive eruptions and ejection of pyroclastics such as tuff and tuff breccia
2 – Flows of andesitic to dacitic lavas with porphyry texture from the volcano edifice. It is probable that eruptions of pyroclastic rocks and lavas were repeated periodically.
3 – Emplacement of subvolcanics and intrusives rocks with compositions of dicitic, andesitic, monzonitic and dioritic nature, respectively.
Fig. 1. Geology map of Kahang area, scale: 1:10,000 showing the Urumieh-Dokhtar magmatic belt and known porphyry deposits there in the belt, based on Shahabpour (1994)
The main structural features are two fault systems trending NE-SW and NW-SE locally, their feather fractures and joints are intense. The main alteration zones (phyllic, argillic and propylitic) were accompanied by the vein to veinlets of quartz, quartz-magnetite and Fe-hydroxides fillings. Mineralization has occurred within intrusives and their host rocks. The ore minerals including chalcopyrite, pyrite, malachite, magnetite, limonite and jarosite, goethite, chalcantite are present and, the latter ones occurred in the intense zone of quartz stockworks and quartz-sericite alteration.

4. Applied P-A fractal model in this case study

For demonstrating the application of the preceding method, 143 lithogeochemical data were taken from Kahang porphyry deposit, NE Isfahan, central Iran. The patterns of Cu, Mo and Au distribution may reflect the variations of the elemental enrichment phases. The power spectra (S) were calculated for the elemental distributions using 2-D Fourier transformation by coding MATLAB application. Logarithmic values of S and A were plotted against each other as shown in Fig. 2. Straight line segments, depicted in Fig. 2, were fitted to the values representing different power-law relationships. Log-log plots, as shown in Fig. 2, there are 3 geochemical populations for Cu and Au and 4 populations for Mo.

Results obtained for other images Cu, Mo and Au have consistently shown that the power spectra of the measures, Cu, Mo and Au possess three different power-law relationships or bifractal properties as observed from the log-log plots. The bifractal properties may imply that multiple geological processes lead the observed the patterns of Cu, Mo and Au. The components with relatively higher frequencies (lower values of S) give larger slopes (2/β > 1) implying that these components may be multifractals whereas the background components with lower frequencies (higher values of S) may correspond to nonfractals or monofractals. The thresholds with relatively higher frequencies (lower values of S) give larger slopes (2/β > 1) implying that these components may be multifractals whereas the background components with lower frequencies (higher values of S) may correspond to nonfractals or monofractals. The thresholds were determined from log-log P-A plots, were depicted in Fig. 2. Based on these thresholds values filters were designed for separation of geochemical populations. Elemental distribution maps were shown in Fig. 3. High intensity Cu, Mo and Au anomalies are located in central parts of the area. Also, several of elemental anomalies were situated in western and eastern parts of the studied area.

5. Comparison with geological particulars

Thresholds were resulted from P-A method are compared and correlated to specific geological parameters of the Kahang porphyry deposit including considering nature of lithological units, faults and alterations. The anomalous parts clearly indicates the main identified faults especially in western and eastern parts of the area which comfortable with existing structural settings and controls as is indicated. Faults intersect the anomalies situated near those structures. On the other hand, faults and elemental anomalies have a proportional relationship. High grade elemental anomalies occurred inside and within the fault zones or located on faults intersection areas. Correlation between Cu anomalies and faults in the Kahang area are shown in Fig. 4.

Correlation of lithological units’ position with elemental distribution maps are shown that high intensity Cu and Au anomalies equaled to higher than 1500 ppm for Cu and 150 ppb for Au covered by monzodioritic rocks but high grade of Mo anomalies, higher than 100 ppm, are
Fig. 2. Log-log plot showing relationships between power spectrum values calculated for Cu (a), Mo (b) and Au (c) and areas with power spectrum above thresholds. Straight-lines were fitted to the values by means of least squares.
Fig. 3. Elemental distributions obtained from applying P-A method. Polygons represent high grade elemental anomalies.

Fig. 4. Cu geochemical distribution maps based on P-A method imposed on fault location maps (red lines).
Fig. 5. Correlation between monzodiorites and high intensive Cu and Au anomalous parts
Fig. 6. Relationship between Cu high intensity geochemical anomalies and potassic alteration (black polygon)
Fig. 7. Relationship between Cu, Mo and Au geochemical anomalies and phyllic alterations (black polygons)
correlated by volcanic andesitic units. In other words, major Cu and Au mineralization occurred concurrent with monzodiorites in final stage of Cu and Au enrichments in central parts of the deposit. Also, volcanic breccias are strong correlation with elemental anomalous parts in western part of the area. Correlation between monzodiorites and high intensive Cu and Au anomalous parts are shown in Fig. 5.

Potassic and phyllic alterations have a strong positive relationship with Cu, Mo and Au anomalies. Potassic alteration covered high intensity Cu anomalies in central parts, as shown in Fig. 6, and phyllic alterations correlated with lower intensity Cu anomalous parts in western and eastern parts. Also, phyllic alterations covered Au and Mo strong anomalies in western parts of the Kahang system (Fig. 7). Geological parameters and settings are shown that elemental anomalies from P-A fractal model have high accuracy.

6. Conclusions

This study in Kahang Cu-Mo porphyry deposit shows that power spectrum-area (P-A) fractal model is a general method for separation between geochemical anomalies and background. Break points in log-log plots observed during fractal modeling may be used to distinguish background and anomalies. Filters constructed on the basis of scaling breaks of power spectra for \( A(S) \) vs. \( S(S-A) \) plots provide a proper way of separating different geochemical populations especially anomalies from background.

Cu, Mo and Au anomalies were separated by P-A model by high accuracy because a very good correlation between the resulted elemental anomalies and geological characteristics. High intensity Cu anomalies were situated in central parts correlated by potassic alteration and phyllic alterations covered elemental anomalies in western and eastern of the area. The occurrence of Cu and Au high enrichments is situated in monzodiorites rocks in central parts of the area. Furthermore, richest parts of these elements correlated to tectonics directionally. Elemental anomalous parts are situated in near, inside or faults intersections.

Acknowledgements

The authors wish to acknowledge Dr. H. Asadi Haroni, Mr P. Rezaeeian and Mr M. Attar for authorising the use of the geochemical data set of Kahang area in Donyaye Mes Company, Tehran, Iran.

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Received: 10 October 2009