Correlation between rock types and copper mineralization using fractal modeling in Kushk-e-Bahram deposit, Central Iran

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Abstract
In this paper, correlation between rock types and Cu mineralization obtained by Concentration-Number (C-N) fractal model calculated in Kushk-e-Bahram Cu deposit, Central Iran. This deposit is located in the Urumieh-Dokhtar magmatic arc (UDMA). The main subject in this study was determination of relation between the Cu grade populations and rock types based on subsurface data using logratio matrix. The C–N log–log plot reveals six geochemical populations which defined by Cu<10 ppm and Cu≥3390 ppm as non-mineralized and high mineralized zones, respectively. According to geological logging and field geology, there are six rock types including tuff and andesitic rocks. Based on the results obtained by logratio matrix, andesite tuff has 87.5% of overall accuracy with Cu enriched zone (Cu≥3390 ppm). Furthermore, pyroclastic tuffs contain Cu grades between 1750 ppm and 3390 ppm as highly mineralized zone. The final results show that the andesite tuff and pyroclastic tuff rocks are main host rocks of this deposit. It would be an important key for copper exploration in the study area and consequently be considered part of the UDMA.

Keywords: Kushk-e-Bahram Cu Deposit; Concentration-Number (C-N) Fractal Model, Logratio Matrix.

Introduction
One of the essential operations for mineral exploration is determination of host rock and related mineralized zones. Assessment of their accuracy and confirmation with geological features in different ore deposits such as determining the mineralization and ore body modeling which support for mining excavation (Cheng et al., 1997; Cheng, 1999; Carranza et al., 2008; Afzal et al., 2011; 2013; 2017; Wang et al., 2011; 2013; Agterberg, 2012; Sadeghi et al., 2015; Heidari et al., 2013; Rahmati et al., 2014; Soltani et al., 2014; Paravarz et al., 2015; Yasrebi et al., 2016). Knowledge for geological and geochemical modeling of different ore deposit types plays a significant role to recognize the geochemical population based on different mathematical methods such as fractal/multifractal modeling (Sim et al., 1999; Carranza, 2009a,b; Carranza and Sadeghi 2010; Nazarpour et al., 2013; Afzal et al., 2014; 2016).

The fractal/multifractal models can be considered as a widely applied instrument in different branches of geosciences which was proposed by Mandelbrot (1983). Various changes in fundamental behavior of phenomenon can be defined by different fractal dimensions (Li et al., 2003; Carranza, 2009a; Afzal et al., 2015, 2017; Zuo et al., 2009; 2016; Hassanpour & Afzal 2013). Several fractal models are widely used in geosciences including Concentration-Area (C-A; Cheng et al., 1994), Concentration-Perimeter (C-P; Cheng, 1995), Concentration-Distance (C-D; Li et al., 2003), Concentration-Volume (C-V; Afzal et al., 2011) and Concentration-Number (C-N; Hassanpour & Afzal 2013).

The first aim of this paper is to delineate and separate the different copper populations in the Kushk-e-Bahram deposit (Central Iran) using the C–N fractal model. Finally, the geochemical zones derived via fractal modeling correlate with rock types for delineation of host rocks by logratio matrix (Carranza, 2011).

Methodology
Concentration–number fractal model
The C-N fractal model proposed by Hassanpour and Afzal (2013) for various anomalies and background separation which can be described as follow:

\[ N (\geq \beta) \propto \beta ^{-\gamma} \]  \hspace{1cm} (1)

where \( N (\geq \beta) \) is the number of a quantity (such as Cu grade in this scenario) greater than \( \beta \) value, which is a value of concentration of study element, and \( \gamma \) is a fractal dimension. The value must not endure any pretreatment, and results can be shown as a C-N log–log plot. This log-log plot represents grade distribution and the relationship among different mineralized zones. It can be correlated
with geological characteristics of ore deposit for different purposes same as a pre-step for grade and geological modeling and estimation (Deng et al., 2010; Sadeghi et al., 2012; Hassanpour & Afzal 2013; Afzal et al., 2016).

Logratio matrix
The logratio matrix established by Carranza (2011) which is a useful implement for calculation of the accuracy and spatial correlation between two binary models (e.g., mineralized zones and rock types). Two types of errors have been determined and can be calculated by anomaly and background values. Type I error (T1E) shows the capability of method in the analysis of the background values, whereas type II error (T2E) indicates the accuracy and the capability of analysis method. However, the parameter that is important in decision making is the overall accuracy (OA) which reveals the correctness of the anomaly and background identification (Table 1).

Geological setting of Kushk-e-Bahram deposit
The Urumieh-Dokhtar magmatic arc (UDMA) is a part of the Alpine-Himalayan orogenic belt which hosts many Cu-Mo-Au porphyry deposits and related ore mineralization types such as Cu manto type (e.g. Shahabpour and Kramers, 1987; Calagari, 2004; Shafiei et al., 2009; Boomeri et al., 2010; Afzal et al., 2012; Aghazadeh et al., 2015; Richards, 2015; Rajabpour et al., 2017; Mosoumi et al., 2017). There are main metallic mineralized zone specifically copper in Iran. Other copper and base metal mineralization types in the UDMA are epithermal systems associated with volcanic rocks especially manto type.

The volcanic-hosted epithermal deposits has been reported mostly from Late Eocene volcanic rocks in the northern part of the UDMA and the vicinity of major faults. These faults are the Takhte-Chaman, Faraj Abad and Abbas Abad faults (Figure 1). There are several copper deposits/mines including Narbaghi, Takhte-Chaman, Zali Bolaghi, Kushk-e-Bahram and Kuh-Pang (Figure 1). The Kushk-e-Bahram deposit occurs as vein-style within Eocene-Oligocene volcanic units which copper mineralization which is hosted by altered rhyodacite and andesitic rocks. Main mineralization is related to copper in the study area. Many of the the Kushk-e-Bahram deposit characteristics including host rock type, mineralization style and associations and hydrothermal alteration halos support its manto origin such as other copper deposits of the study region (Rajabpour et al., 2017). Furthermore, there is a lack of evidences and data for ore mineralization type for the Kushk-e-Bahram Cu deposit.

Based on geological data including surface and subsurface data from 9 boreholes in this deposit, major rock types are pyroclastic tuff, andesite tuff, pyroclastic andesite, clay tuff and soil from pyroclastic tuff rocks (Figure 2).

<table>
<thead>
<tr>
<th>Geological zone</th>
<th>Inside Zone</th>
<th>Outside Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>C–N fractal model</td>
<td>Inside Zone</td>
<td>True positive (A)</td>
</tr>
<tr>
<td></td>
<td>Outside Zone</td>
<td>False negative (C)</td>
</tr>
</tbody>
</table>

Type I error = C/(A+C)  
Type II error = B/(B+D)

Overall accuracy = (A+D)/ (A+B+C+D)

Table 1. Matrix for comparing correlation between the C–N fractal modeling results with geological units (Carranza, 2011).
Figure 1. Location of Kushk-e-Bahram area in Iranian structural map, showing the distribution of the major sedimentary and structural units (after Aghanabati, 1998) and plutonic rocks (after Aghanabati, 1991) and The Urumieh–Dokhtar magmatic arc (UDMA) is mostly of Eocene–Miocene age, some of the other igneous rocks are older. The location of the study area is indicated in the map and Location of the Kushk-e-Bahram Cu deposit and other Cu and Fe deposits within simplified regional geologic map of NE Saveh and prospects of the major metallogenic belt within this zone (modified from Amidi et al., 2006).
Moreover, argillic alteration is extended in this area with assemblages of kaolinite, illite and pyrophyllite. However, propylitic, silicification, jasperoid and iron oxide altered minerals exist in this deposit. There are high amounts oxide ores including malachite, azurite, hematite, magnetic and goethite.

**Discussion**

*Statistical analysis*

There are 9 drill holes for copper exploration in this area. In addition, 149 chip samples from cores with 2 m length. These rock samples were analyzed using ICP-Ms method by Zarazma Company for Cu and related elements (Figure 3). In this study, 5 samples were collected from drill cores and analyzed for quality control (QC) and quality assurance (QA). These results interpreted by T-student and Fisher tests based on means and variances of original and double analysis. Results
derived via these tests indicate that the data have proper accuracy for further modeling and interpretation. The statistical particular for Cu shows that there is not normal distribution (Figure 4 and Table 2). According to this distribution, median can be assumed as first threshold value (Davis, 2002) which is 105 ppm for Cu.

Fractal modeling

The C-N fractal modeling indicates that there are six populations for Cu values with a multifractal nature, as depicted in Figure 5.

Table 2. Principle statistical characteristics for Cu (ppm) in Kushk-e-Bahram deposit

<table>
<thead>
<tr>
<th>No. of observations</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>Median</th>
<th>Variance</th>
<th>Skewness</th>
<th>Variation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>149</td>
<td>4</td>
<td>12032</td>
<td>920.3</td>
<td>105</td>
<td>4.300</td>
<td>3.438</td>
<td>2.25348</td>
</tr>
</tbody>
</table>

Figure 3. Boreholes’ location map in the study area

Figure 4. Histogram of Cu concentration (ppm) in subsurface lithology sample from the Kushk-e-Bahram deposit
First population contains Cu<10 ppm which shows wall rocks without any mineralization. Moreover, main Cu mineralization began from 1778 ppm as third threshold in the C-N log-log plot (Table 3). Enriched zone for Cu mineralization is started from 3981 ppm in this area, as illustrated in Figure 5 and Table 3. Last threshold value is 0.63% for Cu which represents enriched oxide copper mineralization in this deposit (Figure 6).

Table 3. Mineralized zones in the Kushk-e-Bahram deposit based on 9 boreholes of Cu contents defined from the C-N fractal model

<table>
<thead>
<tr>
<th>Mineralized zones</th>
<th>Range Cu (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall rocks</td>
<td>&gt;10</td>
</tr>
<tr>
<td>Weakly mineralized</td>
<td>10-398</td>
</tr>
<tr>
<td>Moderately mineralized</td>
<td>398-1780</td>
</tr>
<tr>
<td>Highly mineralized</td>
<td>1780-3981</td>
</tr>
<tr>
<td>Enriched</td>
<td>&lt;3981</td>
</tr>
<tr>
<td>Extremely</td>
<td>&lt;6310</td>
</tr>
</tbody>
</table>

Figure 5. C-N log-log plot for Cu.

Figure 6. 3D model for Cu distribution
3D model for Cu distribution was constructed using Advanced Inverse Distance Squared (AIDS) by RockWorks 15 software package. Variography and anisotropic ellipsoid were used for this interpolation method. Based on the grid drilling geometry and type of this ore deposit, voxels’ dimensions are 10 m × 10 m × 5 m for X, Y and Z respectively (David, 1970). Main mineralization including highly and enriched zones are located in the northern and southern parts of the study deposit, as depicted in Figure 6. Moderately and highly zones are situated in the central part of the Kusk-e-Bahram deposit (Figure 6).

**Correlation with lithology model**
In this study, 3D lithological model was generated utilizing lithoblending method by the RockWorks software, as depicted in Figure 7. The correlation among different rock types and geochemical populations can consequence for better understanding of copper distribution among different rock types. According to drilling data, the major rock types can be classified as pyroclastic tuff and andesitic tuff. For this purpose, logratio matrix was used and OAs were calculated between geochemical populations and rock types.

In addition, the OA values from the C–N fractal model of mineralized zones were compared with lithological units as follows. Comparison between pyroclastic and andesitic tuffs and enriched/highly mineralized zones from fractal modeling was carried out (Tables 4-8).

### Table 4. Overall accuracy (OA) with respect to the extremely zone (Cu ≥ 6310 ppm) resulted from the C–N fractal model and geological units

<table>
<thead>
<tr>
<th></th>
<th>Pyroclastic Tuff</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inside Zone</td>
<td>Outside Zone</td>
</tr>
<tr>
<td>Extremely zone</td>
<td>Inside Zone</td>
<td>A 9</td>
</tr>
<tr>
<td></td>
<td>Outside Zone</td>
<td>C 7</td>
</tr>
<tr>
<td>OA</td>
<td></td>
<td>0.825</td>
</tr>
</tbody>
</table>

### Table 5. Overall accuracy (OA) with respect to the enriched zone (6310 > Cu ≥ 3980 ppm)

<table>
<thead>
<tr>
<th></th>
<th>Andesite Tuff</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inside Zone</td>
<td>Outside Zone</td>
</tr>
<tr>
<td>Enriched zone</td>
<td>Inside Zone</td>
<td>A 1</td>
</tr>
<tr>
<td></td>
<td>Outside Zone</td>
<td>C 5</td>
</tr>
<tr>
<td>OA</td>
<td></td>
<td>0.875</td>
</tr>
</tbody>
</table>

### Table 6. Overall accuracy (OA) with respect to the highly zone (1780 ≤ Cu < 3980 ppm)

<table>
<thead>
<tr>
<th></th>
<th>Pyroclastic Tuff</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inside Zone</td>
<td>Outside Zone</td>
</tr>
<tr>
<td>Highly zone</td>
<td>Inside Zone</td>
<td>A 12</td>
</tr>
<tr>
<td></td>
<td>Outside Zone</td>
<td>C 4</td>
</tr>
<tr>
<td>OA</td>
<td></td>
<td>0.9</td>
</tr>
</tbody>
</table>

### Table 7. Overall accuracy (OA) with respect to the main zone (Cu ≥ 3980 ppm) in pyroclastic tuff

<table>
<thead>
<tr>
<th></th>
<th>Pyroclastic Tuff</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inside Zone</td>
<td>Outside Zone</td>
</tr>
<tr>
<td>Main zone</td>
<td>Inside Zone</td>
<td>A 9</td>
</tr>
<tr>
<td></td>
<td>Outside Zone</td>
<td>C 7</td>
</tr>
<tr>
<td>OA</td>
<td></td>
<td>0.8</td>
</tr>
</tbody>
</table>

### Table 8. Overall accuracy (OA) with respect to the main zone (Cu ≥ 3980 ppm) in Andesite tuff

<table>
<thead>
<tr>
<th></th>
<th>Andesite Tuff</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inside Zone</td>
<td>Outside Zone</td>
</tr>
<tr>
<td>Main zone</td>
<td>Inside Zone</td>
<td>A 1</td>
</tr>
<tr>
<td></td>
<td>Outside Zone</td>
<td>C 5</td>
</tr>
<tr>
<td>OA</td>
<td></td>
<td>0.517241</td>
</tr>
</tbody>
</table>
In the enriched zone, the logratio matrix represents that the highest value is referring to andesitic tuff with enriched zone (Cu ≥ 0.39%), although pyroclastic tuffs with extremely zone (Cu ≥ 0.63%) have a good values of OA equal to 82.5% and 80%, respectively (Tables 4 and 7). Furthermore, OA between andesitic tuffs and main zone (Cu ≥ 0.39%) is 52% which shows that pyroclastic tuff is major host rock for enriched copper zone in this deposit. However, this zone is correlated with extended argillic alteration and silicification in some parts. Several silicified veins with Cu mineralization are existed according to the structures.

A comparison between highly mineralized zones based on the C-N fractal model and the pyroclastic tuffs in the 3D geological model shows that there is a high OA value equal to 90% (Table 6). However, there is an OA=87.5% between andesitic tuffs and main mineralized zone (0.39% ≤ Cu < 0.63%). Based on this calculation by logratio matrix, pyroclastic rocks are main host rocks with argillic alteration in the Kushk-e-Bahram deposit.

**Conclusion**

Results obtained by this study represent the ability of the C–N fractal model on dealing with complex geological and Cu distribution models in the Kushk-e-Bahram deposit (Central Iran) because of precision, simplicity and computational application and working without any interpolation of original data.

The C–N fractal model revealed six different geochemical populations for Cu which confirm the complex geochemical distribution of Cu. Correspondence between the results derived via the C–N fractal and geological modeling using logratio matrix reveals a high dependency among tuffs specifically pyroclastic tuffs and main Cu mineralized zones (Cu ≥ 0.39%). In addition, these mineralized zones are correlated with argillic alteration zone and silicified in several parts of the mineralization.

Furthermore, it is worthwhile to mention that the good understanding about the correlation among lithological units and Cu grade distribution which can result in better geological and grade modeling in the detailed exploration stage with low volume data collection, thereby decreasing the risk and exploration cost.

**Acknowledgment**

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