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:

$$N(\geq\beta) \propto \beta^{-\gamma} \quad (1)$$

where $N(\geq\beta)$ is the number of a quantity (such as Cu grade in this scenario) greater than β value, which is a value of concentration of study element, and γ 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 Alborz-Azerbaijan magmatic/structural belt (Shamanian *et al.*, 2004; Richards *et al.*, 2006; Kouhestani *et al.*, 2015; Heidari *et al.*, 2015; Mehrabi *et al.*, 2016). Eocene–Oligocene volcanic rocks in the Saveh region (Central Iran), about 104 km SW of Tehran, host several copper deposits/occurrences especially manto type (Figure 1).

A few studies have been carried out on this district and there are some small-scale mining in the past and is explored now (Samani, 1998; 2003; Fazli *et al.*, 2014; 2015; Rajabpour *et al.*, 2015; 2017; Ghaderi *et al.*, 2016; Salehi *et al.*, 2016). A number of researchers suggested an epigenetic volcanogenic origin entitled “Manto type” origin in this region (e.g., Samani, 1998; 2003; Fazli and Ghaderi, 2014; Maghfouri *et al.*, 2015, 2016).

This mineralization occurred within Early to Late Eocene-Oligocene volcanism 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).

Table1. Matrix for comparing correlation between the C–N fractal modeling results with geological units (Carranza, 2011).

		Geological zone	
		Inside Zone	Outside Zone
C–N fractal model	Inside Zone	True positive (A)	False positive (B)
	Outside Zone	False negative (C)	True negative (D)
		Type I error=C/(A+C)	Type II error=B/(B+D)
		Overall accuracy= (A+D)/ (A+B+C+D)	

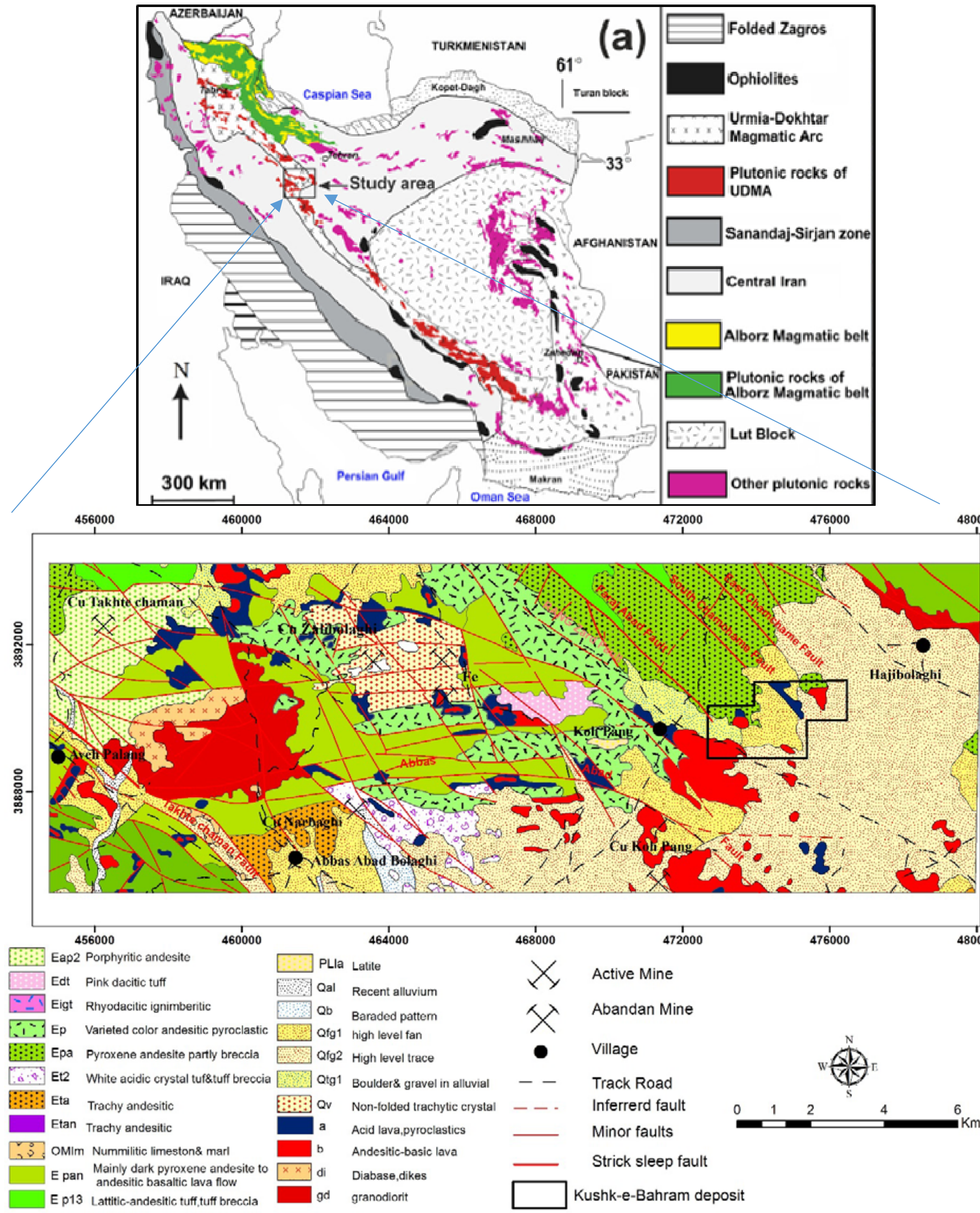

Figure 1. Location of Kushk-e-Bahram area in Iranian structural map, showing the distribution of the major sedimentary and structural units (after Aghanabati, 1998) and plutonic rocks (after Aghanabati, 1991) and The Urumieh–Dokhtar magmatic arc (UDMA) is mostly of Eocene–Miocene age, some of the other 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).

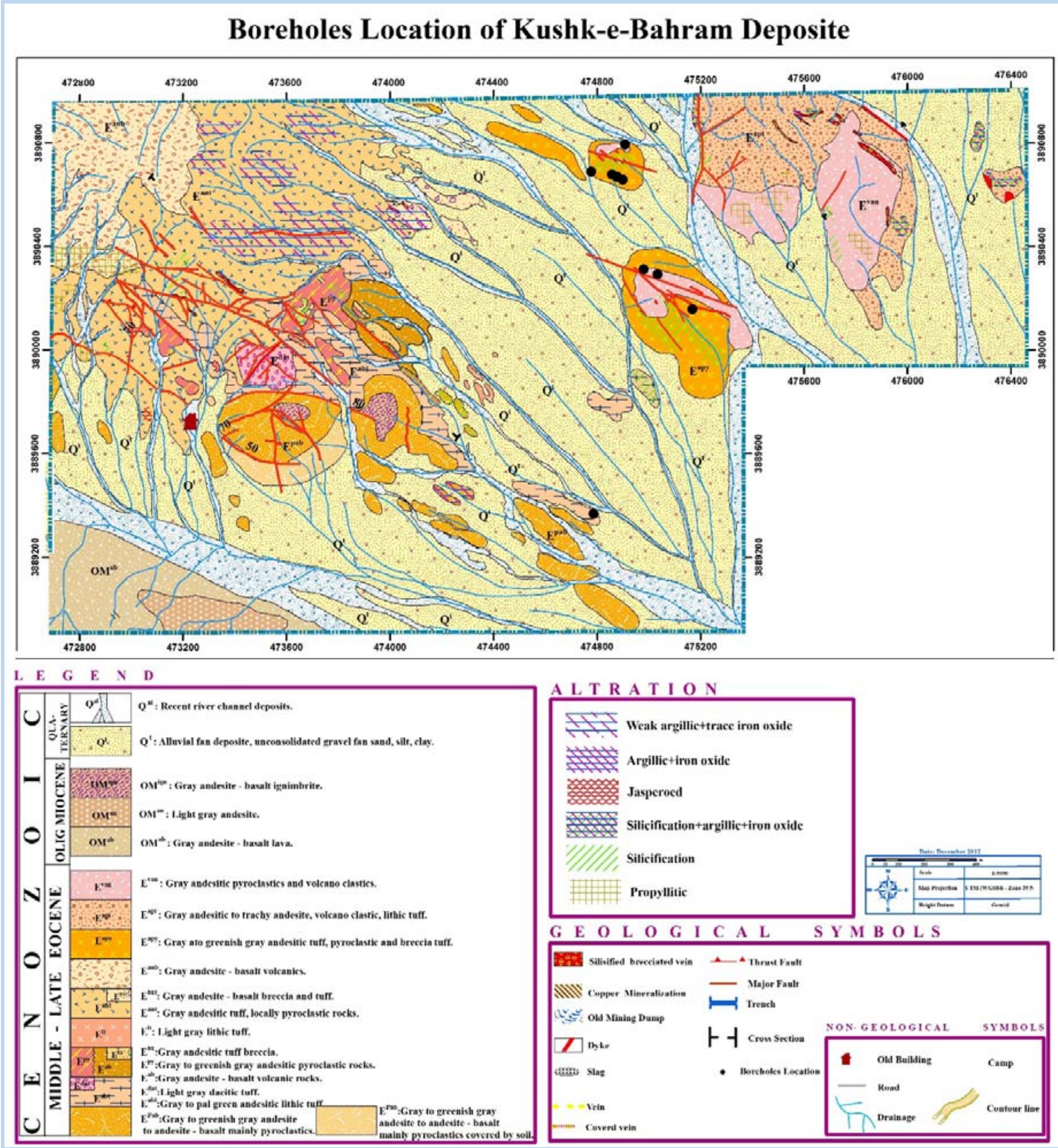

Figure 2. Geological map of 1:5000 Kushk-e-Bahram deposit (Parsi kan Kav Company, 2012).

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

No. of observations	Min	Max	Mean	Median	Variance	Skewness	Variation coefficient
149	4	12032	920.3	105	4.300	3.438	2.25348

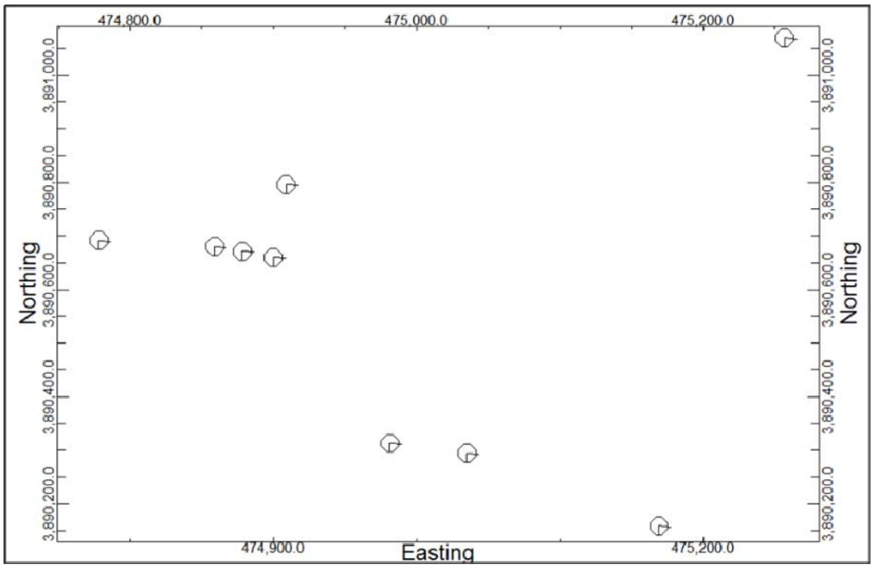

Figure 3. Boreholes' location map in the study area

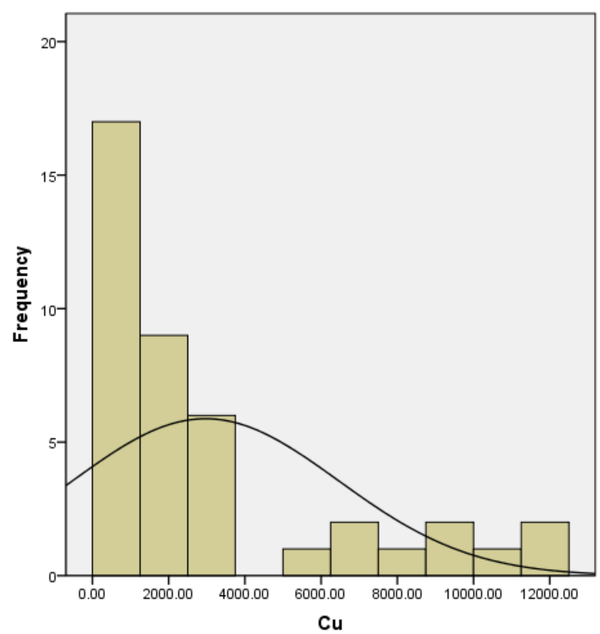

Figure 4. Histogram of Cu concentration (ppm) in subsurface lithology sample from the Kushk-e-Bahram deposit

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

Mineralized zones	**Range Cu (ppm)**
Wall rocks	>10
Weakly mineralized	10-398
Moderately mineralized	398-1780
Highly mineralized	1780-3981
Enriched	<3981
Extremely	<6310

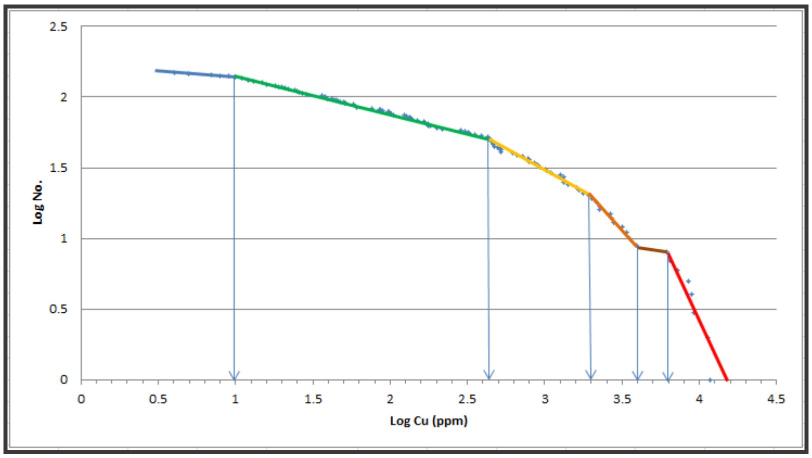

Figure 5. C-N log-log plot for Cu.

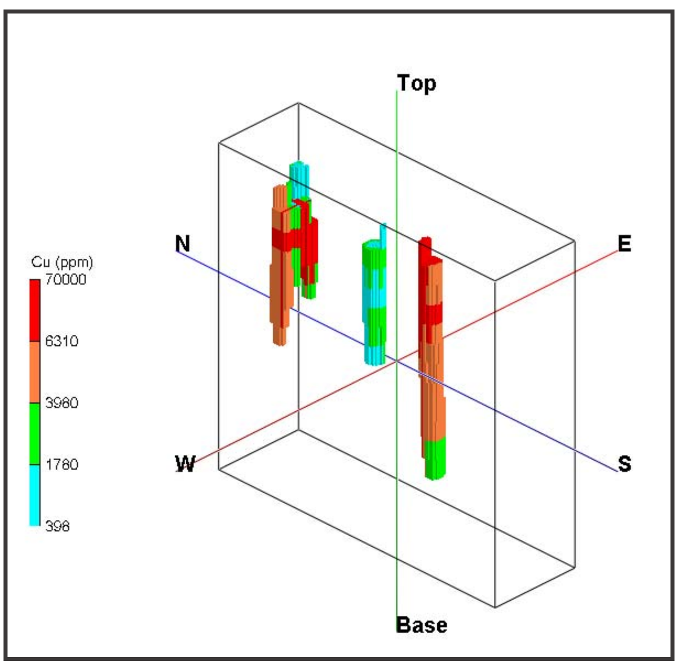

Figure 6. 3D model for Cu distribution

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

		Pyroclastic Tuff	
		Inside Zone	Outside Zone
Extremely zone	Inside Zone	A 9	B 0
	Outside Zone	C 7	D 24
		OA 0.825	

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

		Andesite Tuff	
		Inside Zone	Outside Zone
Enriched zone	Inside Zone	A 1	B 0
	Outside Zone	C 5	D 34
		OA 0.875	

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

		Pyroclastic Tuff	
		Inside Zone	Outside Zone
Highly zone	Inside Zone	A 12	B 0
	Outside Zone	C 4	D 24
		OA 0.9	

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

		Pyroclastic Tuff	
		Inside Zone	Outside Zone
Main zone	Inside Zone	A 9	B 1
	Outside Zone	C 7	D 23
		OA 0.8	

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

		Andesite Tuff	
		Inside Zone	Outside Zone
Main zone	Inside Zone	A 1	B 9
	Outside Zone	C 5	D 14
		OA 0.517241	

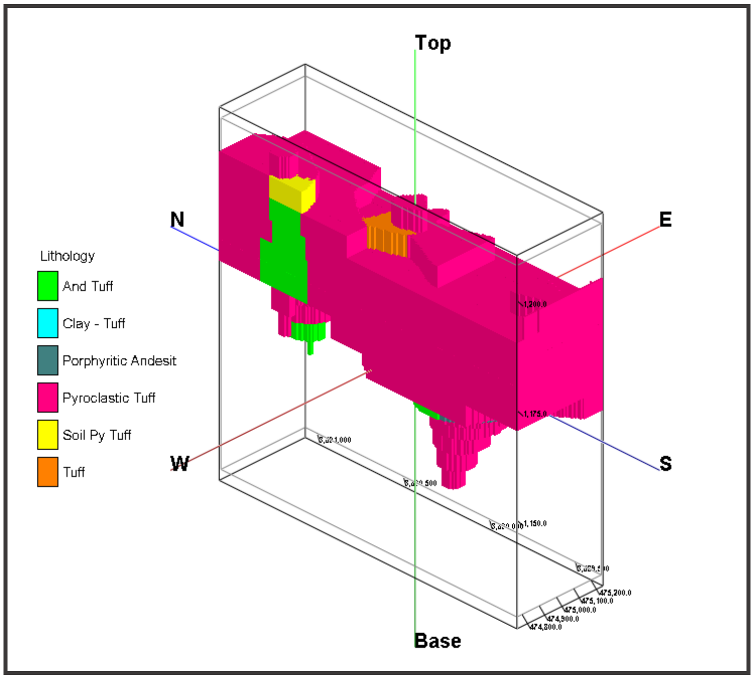

Figure 7. Lithological model of Kushk-e-Bahram deposit

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.

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References

Afzal, P., Fadakar Alghalandis, Y., Khakzad, A., Moarefvand, P., Rashidnejad Omran, N., 2011 Delineation of mineralization zones in porphyry Cu deposits by fractal concentration-volume modeling. J. Geochem Explor., 108: 220-232.

Afzal, P., Fadakar Alghalandis, Y., Khakzad, A., Moarefvand, P., Rashidnejad Omran, N., Asadi Haroni, H., 2012. Application of power-spectrumevolume fractal method for detecting hypogene, supergene enrichment, leached and barren zones in Kahang Cu porphyry deposit, Central Iran. J. Geochem Explor., 112: 131-138.

Afzal, P., Dadashzadeh Ahari, H., Omran, N.R., Aliyari, F., 2013. Delineation of gold mineralized zones using concentration–volume fractal model in Qolqoleh gold deposit, NW Iran. Ore Geol Rev., 55: 125–133.

Afzal, P., Alhoseini, S.H., Tokhmechi, B., Kaveh Ahangarana, D., Yasrebi, A.B., Madani, N., Wetherelt, A., 2014. Outlining of high quality coking coal by Concentration-Volume fractal Model and Turning Bands Simulation in East-Parvadeh Coal Deposit, Central Iran. International Journal of Coal Geology, 127: 88-99.

Afzal, P., Eskandarnejad Tehrani, M., Ghaderi, M., Hosseini, M.R., 2016: Delineation of supergene enrichment, hypogene and oxidation zones utilizing staged factor analysis and fractal modeling in Takht-e-Gonbad porphyry deposit, SE Iran.J. Geochem. Explor., 161: 119-127.

Afzal, P., Ahmadi, K., Rahbar, K., 2017. Application of fractal-wavelet analysis for separation of Geochemical anomalies Journal of African Earth Sciences, 128: 27-36.

Aghanabati, A., 1991. Magmatic rocks of Iran, 1: 2,500,000 survey sheet. Geological Survey of Iran.

Aghanabati, A., 1998. Major sedimentary and structural units of Iran (map). Geological Survey of Iran.

Aghazadeh, M., Hou, Z., Badrzadeh, Z., Zhou, L., 2015. Temporal–spatial distribution and tectonic setting of porphyry copper deposits in Iran: constraints from zircon U-Pb and molybdenite Re–Os geochronology. Ore Geol. Rev., 70: 385–406.

Agterberg, F.P., 2012. Multifractals and geostatistics. J Geochem Explor., 122: 113-122.

Amidi, M.A., Shahrabi, M. and Navaei, Y., 2006. 1: 100,000 Geological map of Zavieh, Geological Survey of Iran.

Boomeri, M., Nakashima, K., Lentz, D.R., 2010. The sarcheshmeh porphyry copper deposit, Kerman, Iran: a mineralogical analysis of the igneous rocks and alteration zones including halogen element systematics related to cu mineralization processes. Ore Geol. Rev., 38: 367–381.

Carranza, E.J.M., 2008: Geochemical Anomaly and Mineral Prospectivity Mapping in GIS. Handbook of Exploration and Environmental Geochemistry, vol. 11. Elsevier, Amsterdam, p. 351.

Carranza, E.J.M., Wibowo, H., Barritt, SD., Sumintadireja, P., 2008. Spatial data analysis and integration for regional-scale geothermal potential mapping, West Java, Indonesia. Geothermics, 37(3): 267–299.

Carranza, E.J.M., 2009a. Controls on mineral deposit occurrence inferred from analysis of their spatial pattern and spatial association with geological features. Ore Geol Rev., 35: 383–400.

Carranza, E.J.M., 2009b. Geochemical anomaly and mineral prospectivity mapping in GIS, vol 11. Elsevier, Amsterdam.

Carranza, E.J.M., 2011. Analysis and mapping of geochemical anomalies using logratio-transformed stream sediment data with censored values. J Geochem Explor., 110 (2): 167–185.

Carranza, E J M., Sadeghi, M., 2010. Predictive mapping of prospectivity and quantitative estimation of undiscovered VMS deposits in Skellefte district (Sweden). Ore Geol Rev., 38(3): 219–241.

Calagari, A. A., 2004. Fluid inclusion studies in quartz veinlets in the porphyry copper deposit at Sungun, East-Azarbaijan, Iran. J Asian Earth Sci., 23: 179-189.

Cheng, Q., 1995. The perimeter–area fractal model and its application to geology. Math Geol., 27: 69–82.

Cheng, Q., Bonham-Carter, G.F., Hall, G.E.M., Bajc, A., 1997: Statistical study of trace elements in the soluble organic and amorphous Fe-Mn phases of surficial sediments, Sudbury Basin. 1. Multivariate and spatial analysis. J Geochem Explor., 59(1): 27–46.

Cheng, Q., 1999. Spatial and scaling modelling for geochemical anomaly separation. J Geochem Explor., 65(3): 175–194.

Deng, J., Wang, Q., Yang, L., Wang, Y., Gong, Q., Liu, H., 2010: Delineation and explanation of geochemical anomalies using fractal models in the Heqing area, Yunnan Province, China. J Geochem Explor., 105 (3): 95–105.

David, M., 1970. Geostatistical Ore Reserve Estimation. Elsevier, Amsterdam. 283 pp.

Davis, J.C., 2002. Statistics and data analysis in Geology. New York: John Wiley and Sons Inc, 638 pp.

Fazli, N., Ghaderi, M., 2014. Petrography, alteration and mineralization at Narbaghi Cu-Ag deposit, NE of Saveh, central part of Urmia-Dokhtar magmatic arc. 18th Sym. Geol. Soc. Iran, 9.

Fazli, N., Ghaderi, M., Maghfouri, S., 2015: Eastern Narbaghi Manto-type stratabound copper mineralization in Eocene volcano-sedimentary sequence, northeast Saveh. Iran. 33th Nat. Geosci. Sym. Iran, 10.

Ghaderi, M., Fazli, N., Yan, S., Lentz, D.R and Li, J.W., 2016. Fluid inclusion studies on North Narbaghi intermediate sulphidation epithermal Ag-Cu deposit, UrmiaDokhtar magmatic arc, Iran, World Multidisciplinary Earth Sciences Symposium (WMESS 2016), Prague (Czech Republic), p. 8.

Hassanpour, S., Afzal, P., 2013. Application of concentration–number (C–N) multifractal modeling for geochemical anomaly separation in Haftcheshmeh porphyry system, NW Iran. Arab J Geosci., 6(3): 957–970.

Heidari, M. Ghaderi, M., Afzal, P., 2013. Delineating mineralized phases based on lithogeochemical data using multifractal model in Touzlar epithermal Au-Ag (Cu) deposit, NW Iran. Applied Geochemistry, 31: 119-132.

Heidari, S.M., Daliran, F., Paquette, J.L., Gasquet, D., 2015. Geology, timing, and genesis of the high sulfidation Au (–Cu) deposit of Touzlar, NW Iran. Ore Geol. Rev., 65: 460–486.

Li, C., Ma, T., Shi, J., 2003. Application of a fractal method relating concentrations and distances for separation of geochemical anomalies from background. J Geochem Explor., 77(2–3): 167–175.

Lima, A., De Vivo, B., Cicchella, D., Cortini, M., Albanese, S., 2003. Multifractal IDW interpolation and fractal filtering method in environmental studies: an application on regional stream sediments of (Italy), Campania region. Appl Geochem., 18(12): 1853–1865.

Mandelbrot, B.B., 1983. The fractal geometry of nature. Freeman, San Fransisco.

Maghfouri, S., Movahednia, M., 2015. Investigation of geology and mineralization of Abbas Abad copper deposit and camper with manto-type deposit. 18th Symposium on Iranian Geosciences. Tarbiat Modares University, Iran (in Persian with English abstract).

Maghfouri, S., Hosseinzadeh, M.R., Moayyed, M., Movahednia, M., Choulet, F., 2016. Geology, mineralization and sulfur isotopes geochemistry of the Mari Cu (Ag) Manto-type deposit, northern Zanjan, Iran. Ore Geology Reviews, 81: 10–22.

Mehrabi, B., Siani, M.G., Goldfarb, R., Azizi, H., Ganerod, M., Marsh, E.E., 2016: Mineral assemblages, fluid evolution, and genesis of polymetallic epithermal veins, Glojeh district, NW Iran. Ore Geol. Rev., 78. 41–57.

Mosoumi, R., Calagari, A.A., Siahsheshm, K., Pichler, Th., 2017: Consideration of geological aspects and geochemical parameters of fluids in Bushdi geothermal field, south of mount Sabalan, NW Iran. Journal of African Earth Sciences, 129: 692-700.

Moeinifar, S., Mohebbi, O., 2012. Geological Map of Kushk-e-Bahram area. Geological Survey of Iran (GSI), Tehran. Scale 1: 5000.

Nazarpour, A., Omran, N., Paydar, G., 2013. Application of multifractal models to identify geochemical anomalies in Zarshuran Au deposit, NW Iran. Arab J Geosci., 8: 877–889.

Percival, T J., Bagby, W C., Radtke, AS., 1988. Physical and chemical features of precious-metal deposits hosted by sedimentary rocks in the western United States. In: Schafer RW, Cooper JJ, Viker PG (edsBulk minable precious metal deposits of the western United States. Geological Society of Nevada, Reno, Nevada 11–34.

Nogol Sadat, A., Hoshmandzadeh, A., 1984. 1: 250,000 Geological map of Saveh, Geological Survey of Iran.

Paravarzar, Sh., Maarefvand, P., Maghsoudi, A., Afzal, P., 2015. Correlation between geological units and mineralized zones using fractal modeling in Zarshuran gold deposit (NW Iran). Arab J Geosc., 8: 3845–3854.

Parsi Kan Kav Company., 2012. 1: 5000 Geological map of Kushk-e-Bahram, Geological Survey of Iran.

Parsi Kan Kav Company., 2012. Final exploration in the Kushk-e-Bahram deposit (in Persian) 65 p.

Rahmati, A., Afzal, P., Abrishamifar, S.A., Sadeghi, B., 2014. Application of concentration–number and concentration–volume fractal models to delineate mineralized zones in the Sheytoor iron deposit, Central Iran. Arab J Geosci., 8: 2953–2965.

Rajabpour, Sh., Behzadi, M., Rasa, I., 2015. Ore mineralogy, hydrothermal alteration and geochemistry characteristics of Kuh-pang volcanic copper deposit in Saveh, middle part of Urumieh -Dokhtar subduction zone. Earth Sci. Res., 25, 109–128 (in Persian with English abstract).

Rajabpour, Sh., Behzadi, M., Jiang, Sh., Rasa I, Lehmann, B., Ma, Y., 2017. Sulfide chemistry and sulfur isotope characteristics of the Cenozoic volcanic-hosted Kuh-Pang copper deposit, Saveh county, northwestern central Iran. Ore Geology Reviews, 86: 563-583.

Richards, J.P., Wilkinson, D., Ullrich, T., 2006. Geology of the Sari Gunay epithermal gold deposit northwest Iran. Econ. Geol., 101: 1455–1496.

Richards, J.P., 2015. Tectonic, magmatic, and metallogenic evolution of the Tethyan orogen: From subduction to collision. Ore Geology Reviews, 70: 323-345.

Sadeghi, B., Moarefvand, P., Afzal, P., Yasrebi, A.B., Saein, L.D., 2012. Application of fractal models to outline mineralized zones in the Zaghia iron ore deposit, Central Iran. J Geochem Explor., 122: 9–19.

Sadeghi, B., Madani, N., Carranza, E.J.M., 2015. Combination of geostatistical simulation and fractal modeling for mineral resource classification. J. Geochem Explor., 149: 59-73.

Samani, B., 1998. Distribution, setting and metallogenesis of copper deposits in Iran. In: Porter, T.M. (Ed.), Porphyry and Hydrothermal Copper and Gold Deposits: A Global Perspective. PGC Publishing, Adelaide, pp. 151–174.

Samani, B., 2003. Metallogeny of manto copper deposits in Iran. 6th Sym. Geol. Soc. Iran, vol. 8.

Salehi, L., Rasa, I., 2016. Sulfur Isotopic Characteristics of the Chalcocite in Madan Bozorg Cu Deposits, Abbas Abad, NE Iran, 34th National and the 2nd International Geosciences Congress, Tehran, Iran.

Soltani Mohammadi, S., Hezarkhan, A., Tercan, E., 2012. Optimally locating additional drill holes in three dimensions using grade and simulated annealing', Journal of Geological Society of India, 80: 700–706.

Shafiei, B., Haschke, M., Shahabpour, J., 2009. Recycling of orogenic arc crust triggers porphyry Cu mineralization in kerman cenozoic arc rocks, southeastern Iran. Miner Deposita, 44 (3): 265–283.

Shahabpour, J., Kramers, J.D., 1987. Lead isotope data from the Sar-cheshmeh porphyry copper deposit, Iran. Miner Deposita, 22 (4), 278–281.

Shamanian, G.H., Hedenquist, J.W., Hattori, K.H., Hassanzadeh, J., 2004. The Gandy and Abolhassani epithermal prospects in the Alborz magmatic arc, Semnan province, Northern Iran. In: Econ. Geol., 99 (4): 691–712.

Sillitoe, R.H., Angeles, C.A, Jr., Comia, G.M., Antioquia, E.C., Abeya, R.B., 1990. An acid-sulphate-type lode gold deposit at Nalesbitan, Luzon, Philippines. J Geochem Explor., 35: 387–411.

Sim, B.L., Agterberg, F.P., Beaudry, C., 1999. Determining the cutoff between background and relative base metal smelter contamination levels using multifractal methods. Comput Geosci., 25(9): 1023–1041.

Soltani, F., Afzal, P., Asghari, O., 2014. Delineation of alteration zones based on Sequential Gaussian Simulation and concentration–volume fractal modeling in the hypogene zone of Sungun copper deposit, NW Iran. J Geochem Explor., 140: 64-76.

Kouhestani, H., Ghaderi, M., Chang, Z., Zaw, K., 2015. Constraints on the ore fluids in the chah zard breccia-hosted epithermal Au–Ag deposit, Iran: fluid inclusions and stable isotope studies. Ore Geol. Rev., 65: 512–521.

Wang, Q., Deng, J, Liu, H., Wang, Y., Sun, X., Wan, L., 2011. Fractal models for estimating local reserves with different mineralization qualities and spatial variations. J Geochem Explor., 108(3): 196–208.

Wang, W., Zhao, J., Cheng, Q., 2013. Application of singularity index mapping technique to gravity/magnetic data analysis in southeastern Yunnan mineral district, China. J Appl Geophys. 92: 39–49.

Yasrebi, A.B., Afzal, P., Wetherelt, A., Foster, P., Madani, N., Jvadi, A., 2016. Application of an inverse distance weighted anisotropic method (IDWAM) to estimate elemental distribution in Eastern Kahang Cu–Mo porphyry deposit, Central Iran. Int. J. Mining and Mineral Engineering, 7: 340-362.

Zuo, R., Agterberg, F.P., Cheng, Q., Yao, L., 2009. Fractal characterization of the spatial distribution of geological point processes. Int J Appl Earth Obs Geoinformation, 11(6): 394–402.

Zuo, R., Wang, J., 2016. Fractal/multifractal modeling of geochemical data: A review. Journal of Geochemical Exploration, 164: 33-41.