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Integration of singularity and zonality methods in preparation of prospectivity map of blind mineralization

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ABSTRACT

Fractal and multifractal singularity are the techniques for detection of depletion and enrichment of elements in geochemical exploration. On the other hand, the index of vertical geochemical zonality (Vz) of Pb.Zn/Cu.Ag is a practical method for exploration of blind porphyry copper mineralization. In this study, these methods are combined for recognition, delineation, and enrichment of Vz in Jebal- Barez in southern Iran. The studied area is located in the Shar-E-Babak–Bam ore field in the southern part of the Central Iranian volcano–plutonic magmatic arc. The region has a semiarid climate, mountainous topography, and a poor vegetation cover. Seven hundred samples of stream sediments were taken from the region. Geochemical data subset represent a total drainage basin area. Samples were analyzed for Cu, Zn, Ag, Pb, Au, W, As, Hg, Ba, Bi by atomic absorption method. Prospectivity map for blind mineralization in this area was prepared. The results are in agreement with previous studies in the region. Kerver was detected as the main blind mineralization in Jebal- Barez which was previously intersected by drilled boreholes in the exploration process. In this research, it was demonstrated that employing the singularity method for zonality separation of geochemical anomalies, as opposed using the singularity of elements, improves prospectivity mapping.

Keywords: *Blind mineralization; Geochemical zonality index; Singularity*

1. Introduction

Identification of geochemical anomalies is one of the most important goals in mineral exploration. In the past 20 years, spatial and non-spatial statistical methods, e.g. Q-Q plot, histogram, probability plot, square diagram and kriging, have been applied for detection of geochemical anomaly [1-5]. Most ordinary statistical methods require the assumption of normal or lognormal distribution. Therefore, such methods may not be effective for exploration of deposits with extreme value distributions [6]. Most of these methods ignore the geometrical information included in geochemical data. Fractal is one the methods that considers the geometrical information. Fractal and multifractal methods are commonly used in detection of irregular geological features.

Local singularity index is based on multifractal method which is effective for detection of local geochemical anomalies and it was introduced by [4, 7]. Recent studies have demonstrated that various types of hazardous geo-processes, such as earthquakes, volcanoes, floods, cloud formation, rainfall, hurricanes, landslides and mineralization processes, often result in anomalous amounts of energy release or mass accumulation that are generally confined to narrow intervals in time or space [6]. The above property of anomalous amounts of energy release or mass accumulation is known as singularity, and these types of processes are considered as singular processes [6, 7]. Singularity is the generic property of non-linear natural process that generates depicting fractality or multifractality [8]. Hydrothermal processes in earth's crust are determined by high concentration of metals with fractal and multifractal processes [9].

Singularity and power low models demonstrated to be suitable for identifying hydrothermal deposits and mapping mineral potentials.

The old methods have disadvantages for exploration of deposits without outcrops or locations covered by desert, forest, regolith, and etc. [10]. Exploration of deep deposits in covered areas is one of the challenges in mineral exploration, because mineral and geological information obtained from such regions are weak and inaccurate.

In recent years, primary haloes were utilized for exploration of blind mineralization [11] Grigorian (1992) presents zonality model for identification of blind mineralization [12]. Other researchers have also used this method for detection of blind mineralization [13-16]. The Vz indices are obtained from ratio of supra-ore elements to sub-ore elements [17, 18]. High value of these indices shows the presence of the

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deposit in lower depths, while low value indicates shows that the deposit was eroded [19].

Many studies have been done by singularity method for detection of local anomaly [6, 8, 10, 20-22]. Cheng (2012) used singularity technique for predicting undiscovered vein or Sn mineral deposits of skarn and hydrothermal types in covered area of Gejiu, Eastern Tianshan, and Xinjiang, China [10]. He calculated the singularity value for Sn element. In the present paper, it is showed that using of singularity for univariate variables is not always sufficient for exploration of blind mineralization. Thus, singularity of Vz index is used instead of singularity of one element for detection of blind mineralization in Jebal-Barez copper deposit.

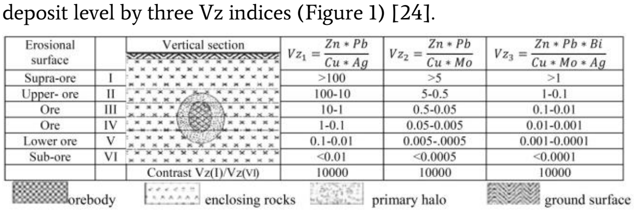
Pervious researchers studied Jebal-Barez for detection of porphyry Cu deposits by various methods (19, 30, 32). Ziaii et al (2011) integrated lithological, structural, alteration, and Vz1 predictor maps by Weight of Evidence (WofE) method. They showed that compared to the Cu map, the Vz map has a stronger spatial association with the discovered porphyry–Cu deposits and is a better predictor of porphyry–Cu prospectivity. Based on the Vz1-in-WofE model, subarea I and II would be favorable mainly for exploration of blind to sub cropping porphyry Cu deposits (Figure 4). In addition, Salimi et al (2011) applied Fuzzy method for integration of geology, geochemistry and remote sensing in this area. Their research showed that subarea I can be ranked as the first and subarea II as the second area for blind mineralization. They reported Kerver as the most important mineralization in this region. The National Iranian Copper Industries Company (NICICo) reported that the drilled boreholes revealed a blind mineralization in subarea I in Jebal-Barez. The outlines of the present paper were verified based on previous reports showing an acceptable agreement with them.

1.1. Methods

The methods applied in this paper are singularity and Zonality methods. In general, producing maps of singularities improve the identification of relatively weak metal concentration anomalies in complicated geological regions. Singularity is used in situations of extensive overlap between background and anomalous values or weak anomalous values concealed within the strong variance of background values. Singularity method uses the surface anomaly in previous researches. Here, singularity method is applied on exploration of blind mineralization. For tackle this problem, singularity method is combined with zonality method. A brief introduction of these two methods is given below.

1.2. Zonality method for exploration of blind mineralization

The primary halo of a mineral deposit is an area including rock, surrounding location of mineral deposit and enriched elements that comprise that deposit [23]. Primary haloes of mineral deposits, which are resulted from the interactions between country rocks and mineralizing fluids, are characterized by element/metal enrichment/depletion. Thus, these haloes are suitable guides for mineral exploration. Vz indices supra- and sub-ore haloes are useful tools at deposit-scales to regional-scale mineral prospectivity mapping [11]. Vz indices show the level mineralization and their primary (supra-ore and sub ore) haloes. Ziaii (1996) presented a model for detection of the deposit level by three Vz indices (Figure 1) [24].



Erosional surface		Vertical section	$Vz_1 = \frac{Zn*Pb}{Cu*Ag}$	$Vz_2 = \frac{Zn*Pb}{Cu*Mo}$	$Vz_3 = \frac{Zn*Pb*Bi}{Cu*Mo*Ag}$
Supra-ore	I		>100	>5	>1
Upper- ore	II		100-10	5-0.5	1-0.1
Ore	III		10-1	0.5-0.05	0.1-0.01
Ore	IV		1-0.1	0.05-0.005	0.01-0.001
Lower ore	V		0.1-0.01	0.005-.0005	0.001-0.0001
Sub-ore	VI		<0.01	<0.0005	<0.0001
		Contrast Vz(I)/Vz(VI)	10000	10000	10000

Figure 1. Vertical geochemical zonality (Vz) models for porphyry–Cu deposits based on typical standard porphyry–Cu deposits in Kazakhstan, Bulgaria, Armenia, and Iran [24].

1.3. Singularity Mapping

In contrast to previous statistical methods, singularity method is the soft threshold technique for identifying the geochemical anomalies [21]. This technique employs the local dynamic thresholds over a study area as well as some window-based contrast singularity maps [22, 25]. Singularity analysis can be used based on continuous pattern to characterize geochemical and geophysical anomalies in which the amount of metals in deposits have pareto tail [20, 26].

Singularity of element is calculated from the average of element concentration C(A) in different sizes of A by means of least squares (LS) fitting of a straight line on log–log paper. These equations are present as follow:

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

$$\log C[A(r_i)]= C_0+ (\alpha-2) \log (r_i) \quad (2)$$

where,

C(A) is the metal concentration for the area A with size of r_i,

C and C_0 are constant,

α is the exponent of the power-law relationship.

According to the equation (1), log (C) versus log (ri) is the line with slope of $\Delta\alpha= \alpha-2$ and y-intercept of C_0. The positive value of slope line ($\Delta\alpha>0$) show the depletion of elements and vice versa. Thus, locations that singularity of them are lower than 2 ($\alpha<2$) show enrichment of concentration elements. Others in which $\alpha>2$, show depletion in concentration of element. More details about this method can be found in [27].

2. Study area

2.1. Geology setting

The study area is located in the Shar-E-Babak–Bam ore field in the southern part of the Central Iranian volcano–plutonic magmatic arc. This region is part of the Sahand-Bazman arc belt. It lies between longitudes 58°00′ and 58°30′ E, and latitudes 28°30′ and 29°00′ N (Figure 2).

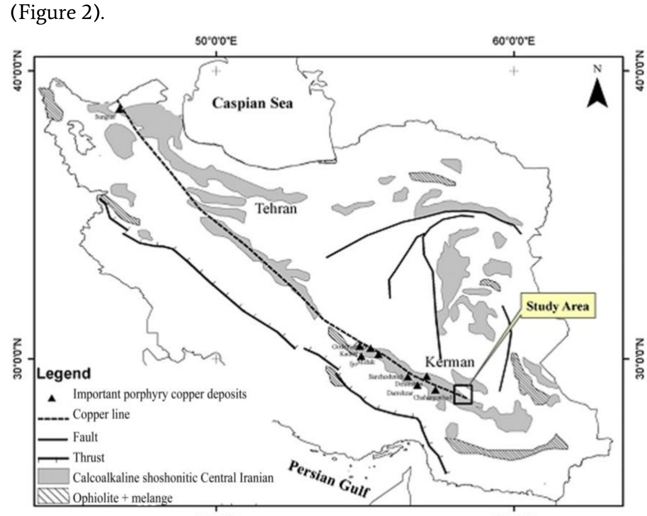


Figure 2. Location of the study area in the southern part of the Sahand–Basman volcanic belt (Iran) [19].

From the geological point of view, this region can be divided into two parts of western north to eastern south sections. The upper section is part of the Bam plain that has been covered by recent sediments. The lower section is part of the Jebal- Barez Mountains that consists of volcanic and intrusive rocks. The NW–SE trending Kuh-e Jebal-Barez mountain ranges, which cut through the study area, form part of the Sahand–Basman Tertiary volcanic belt and metallogenic province within the Central Iranian volcano plutonic magmatic arc. This section contains multiple high mountains, the highest to be around 3741m. There are several perennial rivers in this area. Volcanic activity in the area started from the Late Cretaceous continued to the Middle–Late Eocene [19, 28]. Large masses of granitic and granodioritic outcrops can be found in south and eastern south of the region. In addition to these masses, several dacitic domes were formed in the area. These dacitic domes cover the volcanoclastic rocks. Regional mapping of the Kerman Cenozoic magmatic arc reveals distinctive patterns of argillic and phyllic rocks that can be associated with regional structural features and tectonic processes to be used in regional mineral assessments. Most of the known porphyry Cu deposits in this region are characterized by well-developed zonal patterns of mineralization and hydrothermal alterations. These zonal patterns exhibit significant differences in terms of major oxide and trace element content reflecting variations in mineralogical and geochemical compositions of the mineralized and hydrothermally altered zones. Alteration of the region has been formed around the semi-deep masses and main fractures. According to the intrusive masses, the trend of altered zone is NW to SE. Alterations in the region are Propylitic, Argillic, Silica, Fused Quartz, Potassic, Alunite and Oxide. Mineralization in the area includes Pyrite, Malachite, Azurite, Chalcopyrite, Bornite, Iron Oxides (Hematite, Limonite), and Manganese Oxides (Figure 3) [28].

Two fault systems along the NE and NW were detected in the region. The main fault is along the North West to South East.

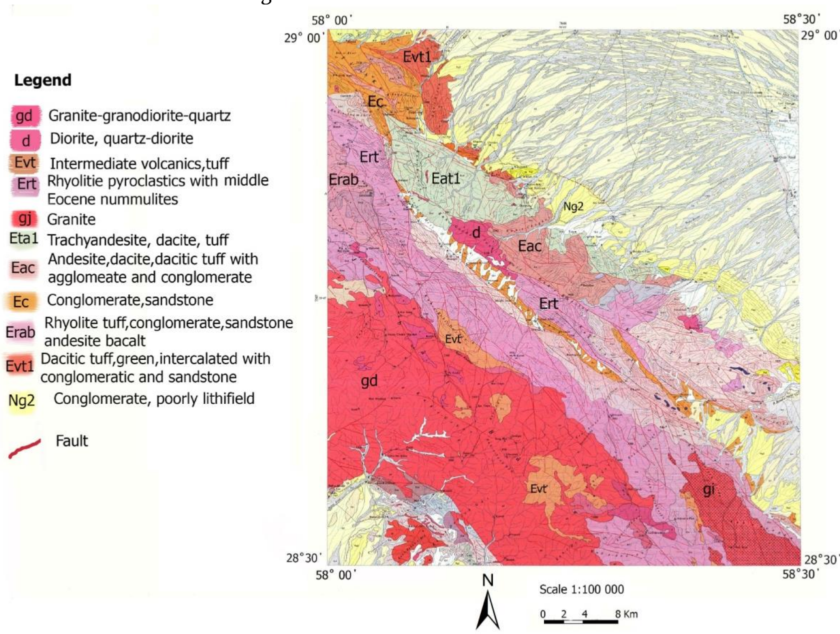


Figure 3. Geological map of the Jebal-Barez area [29].

2.2. Copper deposits

Jebal- Barez is part of the copper belt in the Central Iran. This region is important for its copper and lead-zinc mineralizations. Some of the major deposits in this copper belt are: Sarcheshmeh, Meiduk, DarrehZar, SarKuh, Now Chun.

Fifteen Copper prospects have been detected in the studied area, namely Vouved, Kerver, Gangestan, Gigu, Amjazieh, Zarib, Anarakbala, Deh-darak1, Deh-darak2, Kerver, Sartaghin, Kalsang-Rogeougan, Band-e Razou, Korreh-Darrud, Rudad and DahanehBizgou.

The results of the weight of evidence method by lithology, distance to fault/fracture intersections (m), Alteration, and Vertical Zonality evidences show that Sangestan, Kerver, Deh-darak1, Gigu, Band-e Razou, Korreh-Darrud and Kalsang-Rogeouganare are the blind mineralizations in study region (Figure 4).

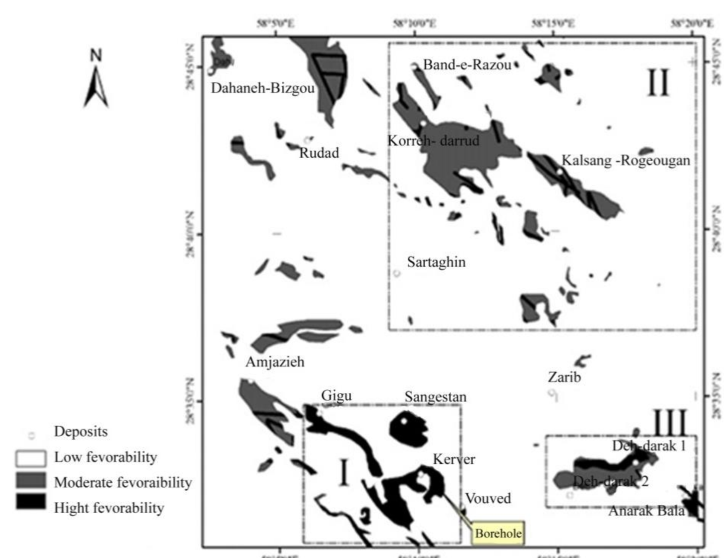


Figure 4. Porphyry–Cu prospectivity models vertical zonality -in-WofE [19].

3. Singularity method and data analysis

In this study, 669 stream sediment samples were collected from the lower section (volcanic and intrusive rocks). The area of interest is around 2500 km^2 though only one sample is taken from each 3 to 4 square kilometers. Samples were analyzed for Cu, Zn, Ag, Pb, Au, W, As, Hg, Ba, Bi by Atomic Absorption method.

The calculations of singularity map were coded in the MATLAB programming Software. The algorithm used in this study is summarized as the following:

1) Generate a grid map by kriging interpolating.
2) Set Seven square windows ranging from 1×1 km^2, 3×3 km^2, 5×5km^2, 7×7km^2, 9×9km^2, 11×11 km^2 to 13×13 km^2.
3) Calculate the average value of element concentration by averaging the values of all samples falling within a window for each window size.
4) Generate two sets of values: average concentration value C[A(ri)] and size of window ri (i=1,...,13) by applying similar processes for each window size centered at the locations one [27,30].
5) Fit a straight line for C[A(ri)] and ri (calculated from previous step) in log-log plot by means of the least square method.
6) Calculate the slope of the straight line that shows the value of $\alpha-2$.

4. Result and discussion

4.1. Singularity of Cu element

Singularity map of Cu is shown in Figure 5. It illustrates that singularity of Cu in Kerver and Sangestan deposits is higher than 2 and Cu is depleted in these deposits. These two deposits are the most important blind mineralizations in Jebal-Barez region which were also confirmed by drilled boreholes; therefore, singularity of Cu in this case provides incorrect results for exploration of blind mineralizations.

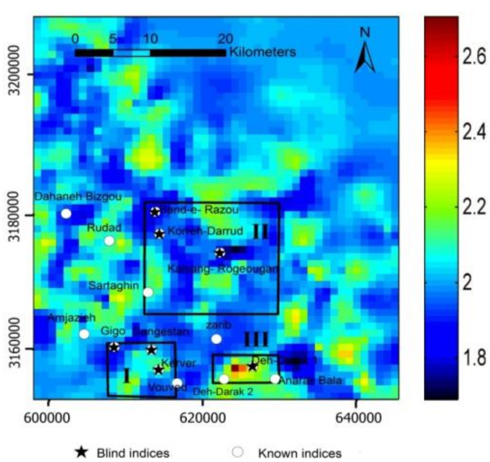


Figure 5. Singularity map of Cu concentration value in Jebal- Barez.

4.2. Singularity map of vertical zonality

Ziaii et al (2011) suggested application of the vertical zonlality instead of Cu concentration for detection of blind mineralization [19]. Among the Vz indices shown in Figure 1, the Vz1 (or Zn×Pb/Cu×Ag) is the best indicator of blind porphyry–Cu deposits (i.e., not enriched with a secondary metal such as Mo or Au) [18, 19, 24, 31].

Singularity of Pb×Zn/Cu×Ag Vz index were calculated and showed its mapping in Figure 6. Singularity value is lower than 2 in several parts of Jebal- Barez that means Vz index is enriched in these parts. The lower value of Vz singularity is in the south of region and in subarea I. Two important deposits of Jebal- Barez are located in this part of the region.

This map introduces the Kerver and Sangestan deposits as two blind mineralization in this region proving the subarea I to be favorable for exploration of blind porphyry Cu mineralization according to Ziaii et al (2011) and Salimi (2011)[19,31]. Blind porphyry Cu mineralization was validated by boreholes drilled in subarea I [19].

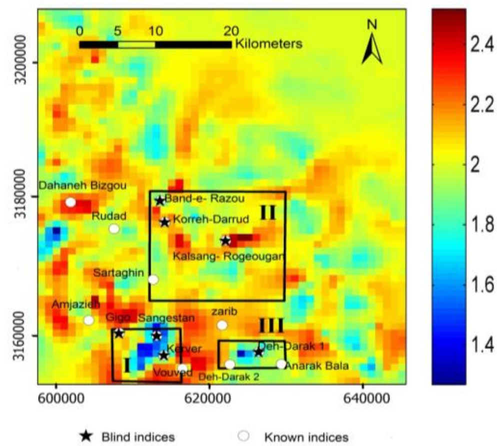


Figure 6. Singularity map of Pb×Zn/Cu×Ag value in Jebal- Barez.

To quantitatively measure the spatial correlation between the areas with α-values less than 2 with the seven known blind mineralizations by Ziaii et al (2011), the weights of evidence method was applied [19,32].

Figure 7 shows the plot of t-value versus singularity value. This plot indicates that the correlation between t-value and α-value is maximum when α=1.65 (1.65 is less than 2), and t-value decreases as α is increased. The highest t-value is 4.52 achieved when α=1.65.

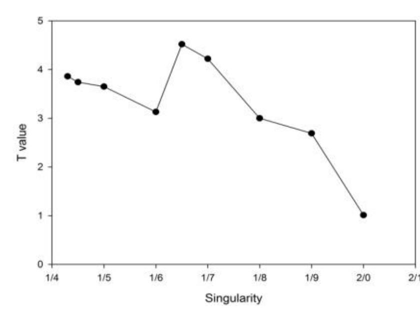


Figure 7. Student's t-value calculated by weights of evidence method for measuring spatial correlation between locations of 7 Cu mineral deposits and areas with α-value below variable thresholds as expressed along x-axis.

The binery singularity map for α<1.65 shows the existing blind mineralizations in southern parts of the region (Figure 8). The results of singularity method are in agreement with the previous literatures [19, 31, 33]. Ziaii et al (2011) used WofE method and reported subarea I and II as high potential parts for blind minralizations, respectively. In addition, Salimi (2011) achieved the same results using the Fuzzy method for the area of intrest [31]. According to the drilled borehole by NICICO (2012) in Jebal- Barez region, blind mineralization is present in subarea I and no other signs of blind mineralizationin can be found in this region [33]. NICICO (2012) recognized no blind mineralization in subarea II which is also confirmed by the results of current research (Table 1).

5. Conclusion

The purpose of this study was detection of blind mineralization in Jebal-Barez in the south of Iran. Blind Mineral deposits and associated primary halos are characterized by variations in chemical compositions along vertical direction. Patterns of Vz around exposed deposits are distinct from that of associated with blind deposits. In this study, the Vz index (Pb.Zn/Cu.Ag) is integrated with singularity method for better understanding of the Vz index enrichment. The results introduced Vz index enrichment in Kerver as the main blind mineralization of this region. This result is in agreement with the outlines of pervious literatures that introduced subarea I and kerver as the main blind mineralizations in the region. Following the results of this study, it is suggested to use singularity of geochemical zonality anomalies instead of contour interpolation, as one of the several evidential maps results to improve mineral prospectivity mapping.

Table 1. Characterizes of blind indices in Jebal- Barez and the surrounding areas.

Indices	Subarea	Geology	Singularity of Vz index	Blind indices base of:			
				WOFE Method [19]	Fuzzy method [31]	Drilling Borehole [33]	Singualrity method in this study
Gigo	I	Granite-Granodiorite-quartz-diorite (JebalBarez granite)	>1.65	*	*	*	-
Sangestan	I		<1.65	*	*	*	*
Kerver	I		<1.65	*	*	*	*
Deh-Darak1	III	Porphyrite with contact phenomena(P)	>1.65	*	-	-	-
Band-e- Razou	II	Rhyoliticpyroclastics (Ert)	>1.65	*	-	-	-
Korreh-Darrud	II		>1.65	*	*	-	-
KalsangRogeougan	II	Agglomerat,ash,tuff (Eta3) Dacite pyroclastic	>1.65	*	-	-	-

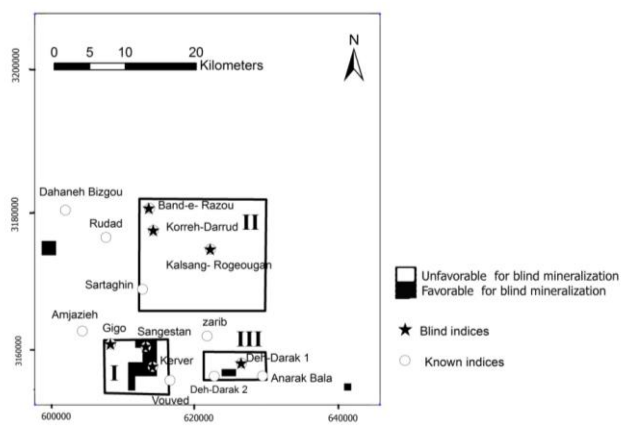


Figure 8. Binery map of singularity map for α value <1.65.

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