An exploratory model for sediment-hosted lead and zinc deposits by using the fractal method in Yazd block- Central Iran

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Abstract

Structure processes have a significant role in forming sediment-hosted lead and zinc deposits. In other words, they are formed in an individual pattern located in the related rift basins. So, the first-order, the second-order, and the third-order basins have been created. Faults operate as the conduct of ore-bearing fluid and the bounding-the second-order basins. By starting rifting, hydrothermal fluid enters a sedimentary basin and as a result of the extending faults, it creates convection cells confined by faults. Therefore, structural processes are the main control factor for these deposits. Also, factors controlling the mineralization are recognized by spatial analysis methods. In this study, to identify controlling factors and present an exploratory pattern for sediment-hosted Pb-Zn deposits in the southern part of the Yazd Block, the fractal (Box- counting) method has been used. This method was utilized to estimate the distance of sub-basins which are the host of sediment-hosted Pb and Zn mineralization for the first time. The results of this method depicted three different populations representing three factors controlling the mineralization in the studied area. These results were consistent with the basin structure which has been formed from three sub-basins. Therefore, three populations obtained from the fractal analysis showed the dimensions of three sub-basins in the studied area. The distance between mineral deposits in the third-order basin obtained about 8 Km while it is about 31 Km for the second-order basins. So, three second-order basins were recognized in which the distance between sub-basin numbers 1 and 2 is about 30 Km while it is about 60 Km between sub-basin numbers 2 and 3. Based on this exploratory model, there could be another second-order basin between sub-basin numbers 2 and 3. According to reports and literature, no other deposit has been discovered between them until now. So, based on the suggested model, there is a possibility of other deposits occurring between sub-basins numbers 2 and 3.

1. INTRODUCTION

Originally, mineral deposits are formed by processes that are associated with geological events [1]. Geological processes consist of hydrothermal fluids, structures, sedimentation, and magmatism [2]. Structure processes that control hydrothermal mineralization act at different scales (regional, local, and prospect). At a regional scale, hydrothermal systems usually form in particular tectonic settings. At a local system, hydrothermal deposits depict the proximity to shear zones or regional faults, acting as pathways for transporting ore-forming fluids from deep sources to deposition environments. At a prospect scale, breccias, veins, and hydrothermal replacement disseminations act as favorable environments for depositing ore-forming fluids and forming mineral deposits [3]. In the same way, the sediment-hosted Pb and Zn deposits are formed about structures in the specific pattern in rift basins. The three sub-basins which are related to structure processes are formed by starting and following rifting events [4].

So, these structure factors spatially main faults are very important in sediment-hosted Pb and Zn exploration, because exploration is limited to areas where control processes are concentrated [1]. Furthermore, deposits that are associated with hydrothermal fluids exhibit a spatial relationship with structural features [5]. Since mineral occurrences are simplified to be denoted as points on large-scale maps in different applications of spatial analyses, spatial analysis's methods for point patterns have been increasingly employed to study geological controls of mineral deposits and spatial distribution, generally including fractal geometry analysis [3]. It is also notable that the aim of fractal geometry application to geological features is to discover systematic patterns and their correlation to geologic processes[1]. Therefore, it can be recognized the relationship between sediment-hosted Pb and Zn deposits and structural controls by using fractal analysis and it is possible to present a pattern for exploration objectives by recognizing this relationship.

Generally, the fractal method is used in a lot of geological studies such as geophysics, assessment of fault zones, the surveying topography of the ocean floor, and geochemistry [6]. Box-counting is a fractal method that is used in the spatial analysis of mineral deposits. This method is used to identify the control processes of mineralization in regional and local scales in different kinds of deposits [7-10]. The fractal behavior of different mineral deposits such as porphyry copper, precious metal, and polymetallic veins was investigated by Raines [11]. Results showed that the spatial distribution of deposits follows fractal rules. Also, Carlson [12] has used this method for 4775 precious metal deposits in Basin and Range provinces. Based on his results, the distribution of deposits created due to hydrothermal systems in all scales is fractal. Furthermore, the box-counting method was utilized for the spatial distribution of VMS in the Spanish Iberian Pyrite Belt. The results depicted that the behavior of deposits is fractal. Also, the concentration of mineral deposits is controlled by complex geological factors such as the distribution of host lithology, fractures, and hydrothermal systems [13]. In recent years, this method is used for IOCG deposits and MVT deposits in Brazil and central Iran, respectively [1, 14]. The results showed that the distribution of deposits affected by regional and local processes has been followed the fractal pattern. As well, the box-counting method was used for the recognition of structural controls on porphyry Cu mineralization in the Dehaj area, central Iran [15]. In similar research, the relationship between structures and Cu mineralization in the Saveh region has been investigated in which results depicted that mineralization is associated with faults [5]. Furthermore, the fractal nature of structural controls on ore formation of Iron Oxide Copper-Gold Deposits in the Carajás Mineral Province, Brazilian Amazon has been studied. The results showed that structures are a dominant factor controlling fluid flow [16]. Eventually, the fractal analysis showed that there is a relationship between Pb-Zn mineralization and Behabad fault [2].

The pattern presented structurally for sediment-hosted Pb and Zn deposits includes three sub-basins that they have related to each other spatially. The controlling factor is structure processes in forming these deposits. On other hand, it can be recognized the relationship between sediment-hosted Pb and Zn deposits and structural controls by using fractal analysis. Consequently, the distance of sub-basins can be estimated by fractal analysis which is the numerical method. Therefore, the goal of this study is the estimation of the distance of sub-basins that are the host of sediment-hosted Pb and Zn deposits by the fractal method. The past studies have identified structure processes (regional, local, and prospect) that control mineralization qualitatively. But, in this study and for the first time, this method is used to discover the relationship between the formation of sediment-hosted Pb and Zn deposits and their structure process quantitatively. It is expected that we can be able to present an exploratory model for the un-discovered deposits.

Despite being more than 285 sediment-hosted lead and zinc deposits in Iran, just a few of them have been explored or extracted [17]. The deposits of various ages are located in different structure zones of Iran. Deposits formed in the Cretaceous age are mainly located in the Yazd-Anarak metallogenic belt (YAMB) and Malayer-Esfahan metallogenic belt (MEMB). The last one has been considered more and was studied. In contrast, exploration researches on YAMB have been limited to special deposits such as Mehdiabad and Nakhlak [18, 19]. So, the southern part of the Yazd-Anarak metallogenic zone was selected for studying the spatial distribution of sediment-hosted lead and zinc deposits by the fractal (box-counting) method. The host rocks of these deposits are carbonate sediments of the Taft Formation back to the Early Cretaceous age. Since the Taft Formation is the host rock of all these deposits, it is expected that they have spatial relationships together.

2. GEOLOGY SETTING

Studied lead and zinc deposits are located in the southern Yazd block, westernmost of Central-

East Iranian Microcontinent (CEIM). This block is bounded by the Dehshir-Baft fault to the west and by and Anar fault to the east (Figure 1b). The stratigraphy of the southern Yazd block is similar to other parts of CEIM [20]. The late Neoproterozoic metamorphic rocks of the Boneh-Shurow basement complex are exposed in Yazd block but this complex has not been observed in the southern part.

The Ordovician to Permian rocks overlies on the Neoproterozoic to Cambrian sedimentary rocks of Kahar, Rizu, Deso, and Barut Formations [21]. The Paleozoic Formations are overlain by the Triassic to Jurassic sedimentary rocks consisting of Shotori, Nayband, and Shemshak Formations [21]. The sediment-hosted Pb and Zn deposits have been located in formations with the Early Cretaceous age. Therefore, the Early Cretaceous rocks in the southern part of the Yazd block include Sangestan, Taft, and Darreh-Zanjir Formations that were introduced by Nabavi [22]. The Sangestan Formation consisting of sandstones and conglomerates has filled a pronounced palaeo-relief of basement rocks of the Shir-Kuh granite (Late Jurassic) or the metamorphic Shemshak Group (Upper Triassic – Middle Jurassic) [23]. The Taft Formation, which consists of dark-colored sandy, thin-bedded to massive dolomite and limestone with abundant rudists and orbitolinids, conformably overlies the Sangestan Formation [24]. The Darreh-Zanjir Formation which is composed of spiculitic limestones and deep-water marls is the topmost Lower Cretaceous rock unit in the southern Yazd block [23]. The Kerman Conglomerate un-conformably overlies the Cretaceous sediments. Finally, Cenozoic geological units are also located in the large parts of this block [21]. The southern Yazd block geological map is shown in Figure 1b.

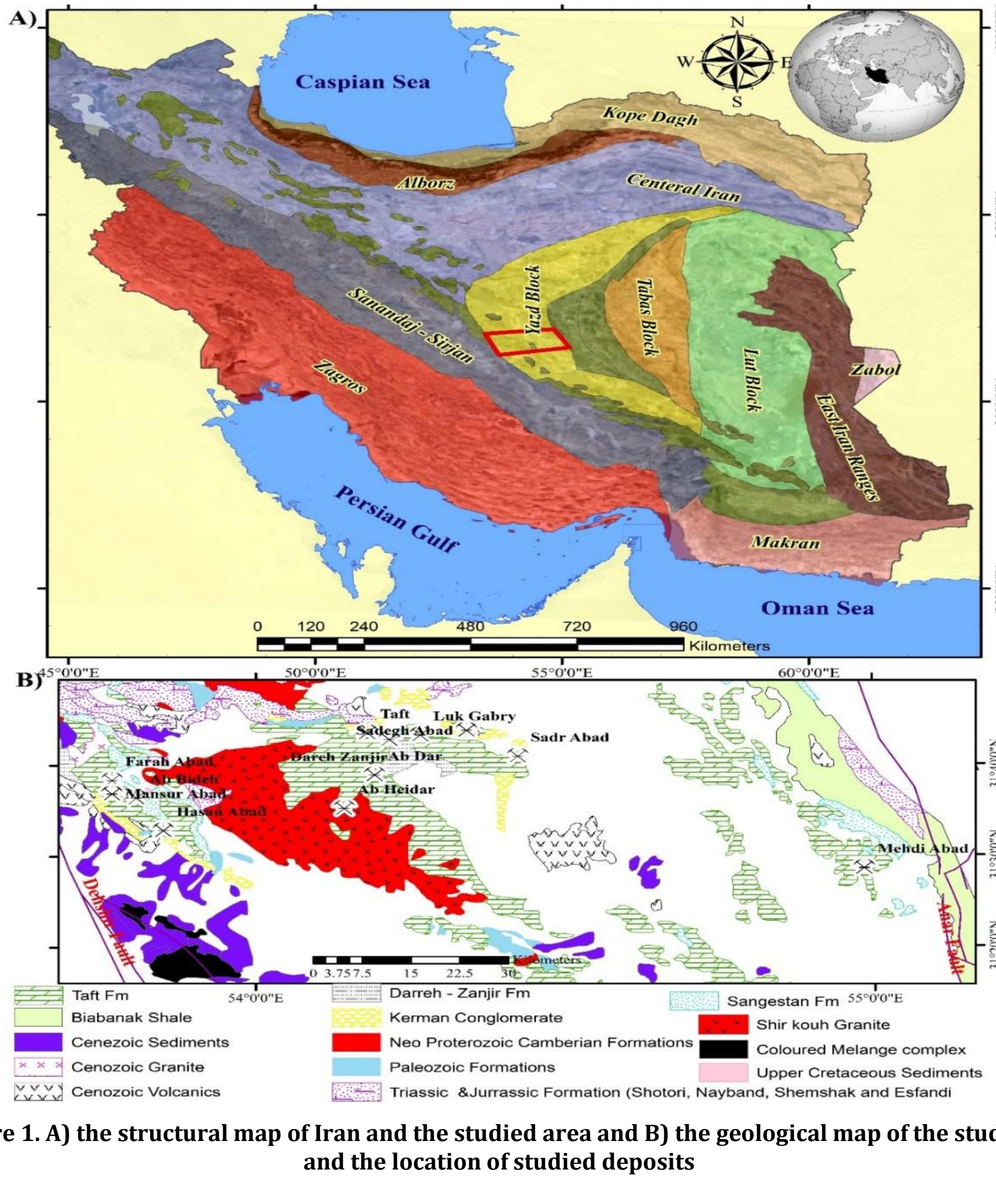

Figure 1. A) the structural map of Iran and the studied area and B) the geological map of the studied area and the location of studied deposits

3. BOX-COUNTING FRACTAL METHOD

The fractal term is described by Mandelbrot and Wheeler [25] to describe a pattern including parts that have geometries (e.g., form or shape), regardless of the scale or size, that are less or more similar to the whole pattern. If the pattern dimension (Df) exceeds its topological or Euclidean dimension (D), it is considered to be fractal. For instance, a fractal line (e.g., a coastline) does not have D=1 as expected from Euclidean geometry but has a Df between 1 (D for a line) and 2 (D for an area) [26]. Therefore, a fractal is commonly revealed through its fractal dimension, representing a measurement of object irregularity [16]. There are various fractal methods for discriminating the different populations in earth science such as concentration-area, concentration-distance, concentration-volume, spectrum-area, and size-number [27]. The fractal dimension of the spatial pattern of a point set can be obtained by the box-counting method which was presented by Mandelbrot [28]. In this method, a square grid with a cell size δ is overlaid on a map of points. The number of cells, n (δ), including one or more points is counted. The procedure is repeated for various values of δ (Figure 2) and the results are plotted in a log-log graph [26].

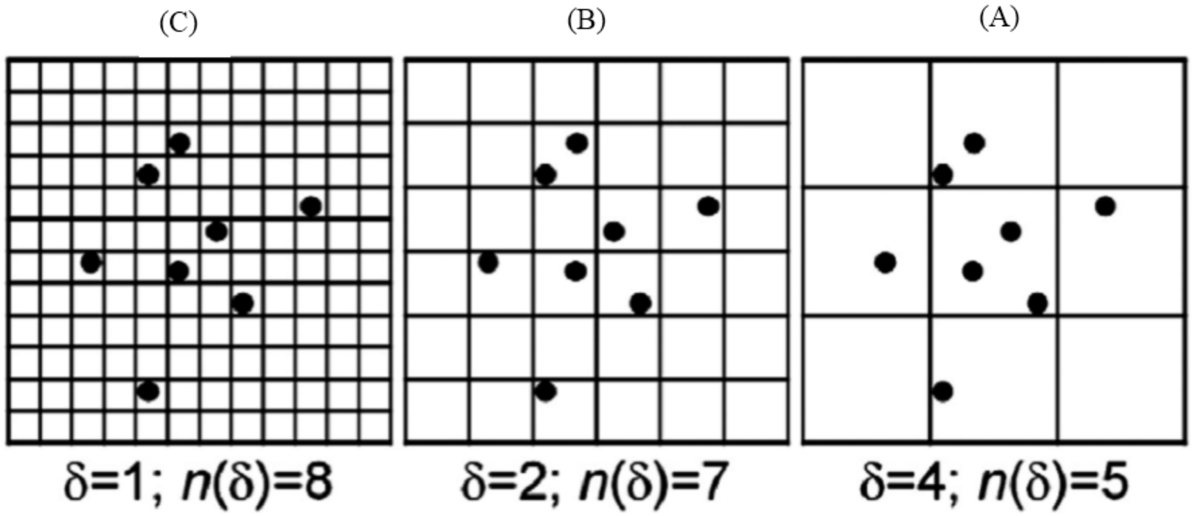

Figure 2. an example of the box-counting method [26]: (A) 5 cells containing target points with cell size δ=4; (B) 7 cells counted with cell size δ=2; (C) 8 cells counted with cell size δ=1

The plots of n (δ) versus δ can be described by a power-law function if the spatial pattern of the points is fractal, therefore [28]:

$$n(\delta) = C\delta^{-Db} \quad (1)$$

Where; C is the constant of proportionality between δ and n (δ) and Db, varying between 0 and 2, is the box-counting fractal dimension.

The relation in Eq. (1) can be represented as a linear function in a log-log graph as follows:

$$log\, n(\delta) = log\, C - D_b\, log\, \delta \quad (2)$$

The slope, D_b, of the linear log-log plots of n(δ) versus δ represents a measurement of the fractal dimension of the spatial pattern of a set of points [26].

4. RESULTS

To investigate the relationship between sediment-hosted Pb-Zn deposits in the southern part of Yazd block, fractal analysis using the Box-Counting method was utilized. The host rock of these deposits is Taft Formation back to the Early Cretaceous age. The spatial coordinates of deposits and their features have been shown in Figure 1b and Table 1, respectively.

Table 1. the specifications of sediment-hosted Pb-Zn deposits with Cretaceous age in the southern part of Yazd block. CH: Carbonate Hosted

Number	Deposit name	Deposit Type	host rock age	Reference
1	Sadegh Abad	CH Zn-Pb	Early Cretaceous	[29]
2	Taft	CH Zn-Pb	Early Cretaceous	[17]
3	Farah Abad	Sedex	Early Cretaceous	[30]
4	Mansur Abad	Sedex	Early Cretaceous	[30]
5	Dareh Zanjir	MVT	Early Cretaceous	[31]
6	Sadr Abad	CH Zn-Pb	Early Cretaceous	[17]
7	Luk Gabry	?	Early Cretaceous	[17]
8	Mehdi Abad	Sedex	Early Cretaceous	[20]
9	Hasan Abad	?	Early Cretaceous	[29]
10	Ab Bideh	?	Early Cretaceous	GSI (unpublished report)
11	Ab Heidar	?	Early Cretaceous	GSI (unpublished report)
12	Ab Dar	?	Early Cretaceous	GSI (unpublished report)

To carry out the box-counting method, the research area including all deposits was overlain by a grid that involves boxes or square grid with side length 125 Km, and then the number of those cells which contain the part of feature (mineral deposit) was counted. This process was repeated by using different cell sizes in six stages to obtain corresponding cell numbers. The results of this method are shown in Table 2.

Table 2. the results of box-counting on sediment-hosted Pb-Zn in Yazd block

Number	Size (δ) (Km)	Number of cells with deposits n (δ)
1	125	1
2	62.50	2
3	31.25	6
4	15.63	7
5	7.81	10
6	3.91	11
7	1.96	12

The result of the box-counting method i.e., log n (δ) versus log δ graph, has been represented in Figure 3.

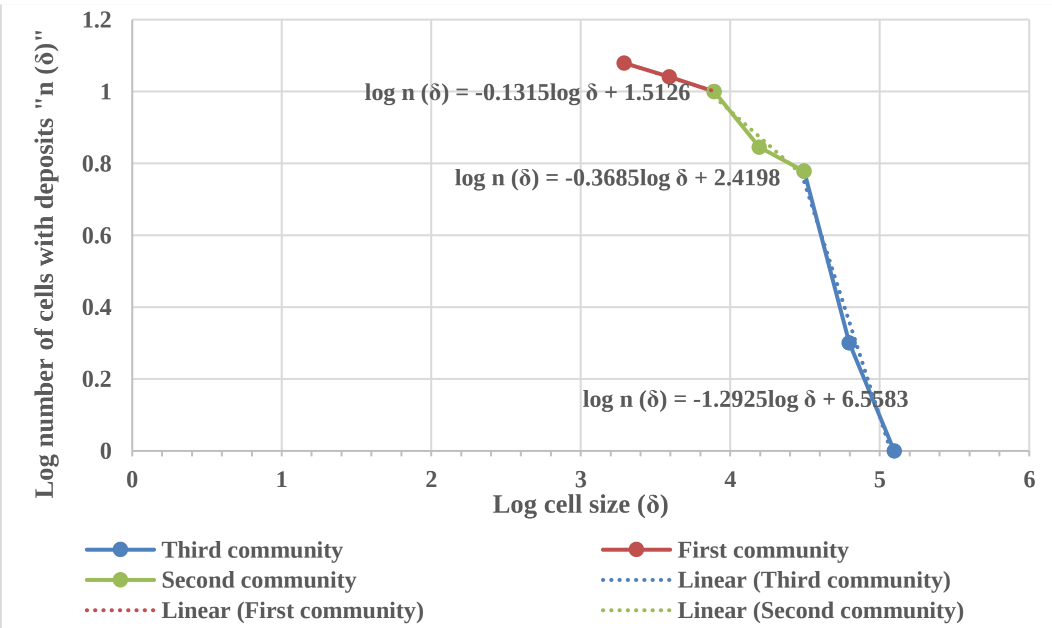

Figure 3. the plot log n (δ) versus log δ manifesting three spatial patterns of sediment-hosted deposits in the Yazd block

This analysis yields a fractal pattern, as indicated by three regression lines that represent three fractal dimensions (the slope line) varying from 0.13 (δ ≤ 8 km), 0.36 (between 8 and 31 km) to 1.29 (δ> 31 km). As it can be seen in Figure 3, the graph has two breakpoints that represent three different populations for the distribution of these deposits.

5. DISCUSSION

The box-counting log-log graph depicted that the spatial distribution of sediment-hosted Pb and Zn deposits in the studied area is not random, but it has been followed the fractal pattern. The log n (δ) versus log δ graph on sediment-hosted Pb and Zn deposits showed that mineral deposits have three individual populations and two breakpoints (Figure 3).

Furthermore, the obtained fractal dimensions characterize different aspects of the geometric complexity of the geological processes, which control the mineralization in the studied area. Thus, the higher value of this dimension represents the more complexity of the mineralization controlling process. In other words, it is considered that differences in fractal dimensions are plausibly related to various geological controls which operate at different scales, e.g., regional-, local- and prospect-scale. As a result, the structural controls of these deposits acted at scales of lesser than 8Km, 8-31Km, and greater than 31 Km representing prospect-, local-, and regional scale, respectively.

These results are consistent with the relationship between basin architecture and SEDEX deposits that has been presented by [32] and verified by later studies such as [33-35]. Based on this model, these deposits are formed in an individual pattern related to rift basins. SEDEX deposits have been formed in extensional, first-order intra-cratonic, and epi-continental basins that exceed about 100 kilometers (km) in diameter. Within first-order basins, the second-order basins are controlled structurally by half-graben structures. The dimension of these sub-basins is about tens of kilometers. The graben-bounding faults act as conduits for hydrothermal brines which travel from the underlying strata onto the seafloor to form the deposits. The third-order basins which are a few kilometers in diameter represent low-energy depositional environments that provide favorable locations for metalliferous brines to accumulate and form deposits [4].

Results of the fractal method discriminated the mentioned three basins in the studied area. The first-order, second-order, and third-order basins in the studied area are greater than 31 Km, about 8-31Km, and about 8Km in diameter, respectively. Also, three geological processes have been controlled mineralization in the southern part of Yazd block; by starting rifting, the first-order basin is formed and a great hydrothermal system entered the basin (regional process). As result a rifting, horsts, and grabens (the second-order basins) have been formed that are limited by faults (local process). So, the faults cause the hydrothermal system to turn into convection cells. The convection cell for sediment-hosted deposits has been presented by [36] in which hydrothermal fluids enter into the basin and it creates convection cells due to faults (Figure 4). Hydrothermal fluids which arise along the faults have deposited in low-energy environments (the third-order basins) and it has been formed sediment-hosted Pb and Zn deposits in the southern part of the Yazd-Anarak belt (prospect processes).

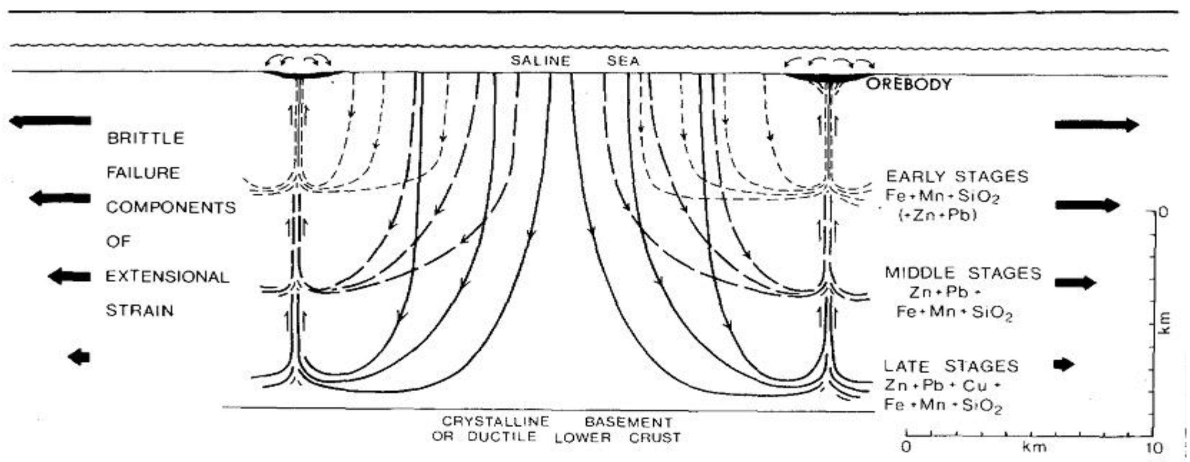

Figure 4. a general model of convection cells of hydrothermal fluid for SEDEX deposits (after [36])

Therefore, we can consider three second-order basins, which have been formed in a first basin, in the studied area as shown in Figure 5. In each second-order basin, individual lead and zinc deposit has been formed into the third-order basin, (i.e. individual deposition environment). The second-order basin number1 including Farah Abad, Mansour Abad, Hasan Abad, and Ab Bideh deposits has been located about 30 Km from the second-order basin number 2. Also, the distance between deposits which have located in this sub-basin is about 8Km (i.e. each deposit has formed into a third-order basin). In the same way, the second basin number 2 consist of Ab Heidar, Ab Dar, Darreh Zanjir, Taft, Luk Gabri, and Sadr abad deposits. The second-order basin number 3 consist of Mehdi Abad deposits. On the other hand, based on previous studies, faults have a significant role in the formation of sediment-hosted Pb and Zn deposits in the southern part of the Yazd block [20, 30, 31, 37]. It is consistent with the model presented in which faults act as the conduct of ore-bearing fluids in the second-order basins. These faults which have confined the sub-basins have been shown in Figure 6.

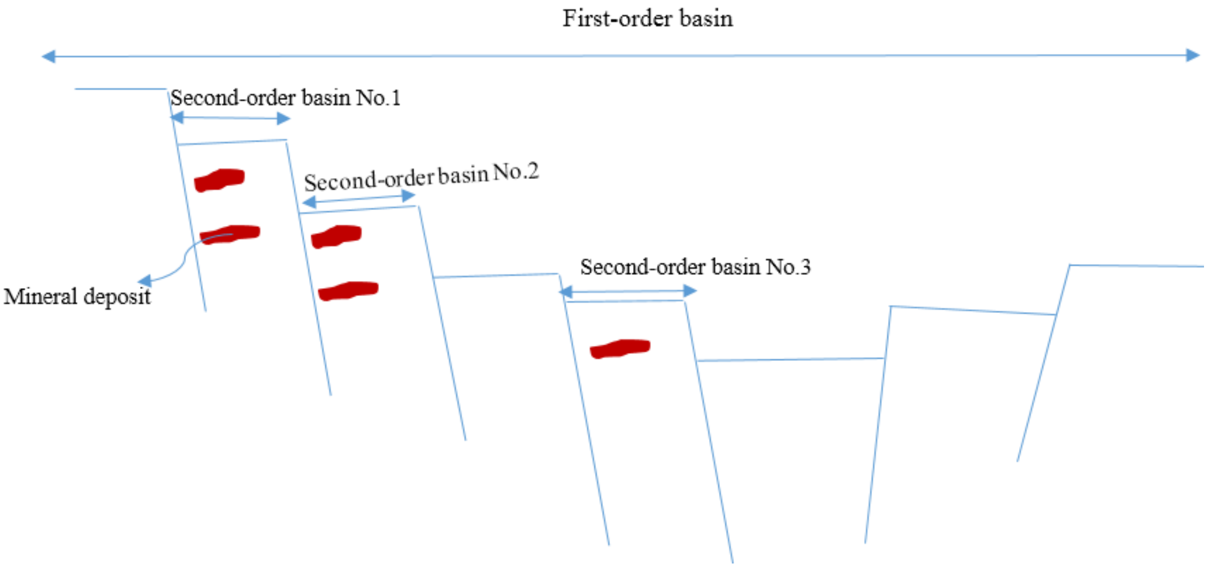

Figure 5. the model presented for sediment-hosted lead and zinc deposits based on fractal analysis in the southern part of Yazd block

6. PRESENTING AN EXPLORATORY MODEL

If the model shown in Figure 5 is generalized to the area containing Sedex deposits in this research, the distance between two second-order sub-basins is assumed to be about 31Km based on fractal results. But the distance between sub-basin numbers 2 and 3 is about 60 Km that indicative of existing another second-order basin between them. So, according to the reports and literature, no other deposit has been discovered between them until now. So, based on the suggested model, there is a possibility of other deposits occurring between sub-basins numbers 2 and 3. The faults which are conducted for forming lead and zinc deposits have been identified in Figure 6. They are confining the second-order sub-basins in the studied area. Therefore, the suggestive area for un-discovered deposits has been depicted in a blue rectangle.

For validating the model, based on reports of Geological Survey and Mineral Exploration of Yazd branch and the Industry, Mining and Trade organization of Yazd Province has not been observed Pb and Zn index in the suggestive area. Since there are these deposits with the distinctive pattern in the Taft formation in the other areas, it will increase the probability of existence sediment-hosted Pb and Zn deposits in the suggestive area. Furthermore, based on an oral conversation with former experts of the Mehdiabad mine, there is evidence of ancient mining inside the Taft Formation which is located in the back of Abolfazl Mosque that is located in the suggestive area.

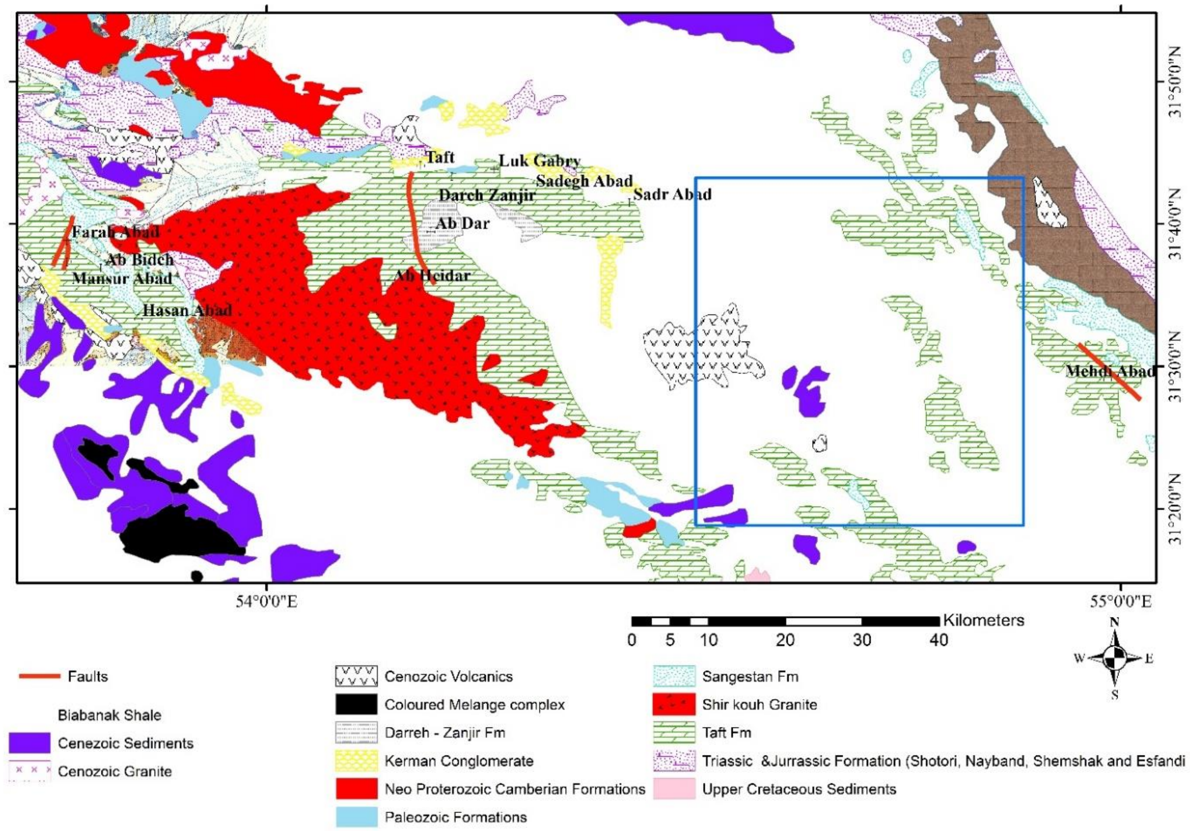

Figure 6. the suggestive area for exploration of undiscovered deposits based on the combination of fractal analysis and accepted pattern foe sediment-hosted Pb and Zn deposit (blue rectangle)

7. CONCLUSION

Fractal analysis using the box-counting method was utilized to provide an exploratory model for sediment-hosted Pb-Zn deposits with Early Cretaceous age in the southern part of Yazd block. In addition, the distance of sub-basins that are related to sediment-hosted Pb and Zn deposits in a rift tectonic environment has been estimated for the first time .

Based on the results, it can be said these deposits displayed fractal behavior with two breakpoints of approximately 8 Km and 31Km and indicated that three types of processes have been effective in the deposit formation. Prospect- local-, and regional- processes have affected less than 8 km, between 8 -31, and further than 31 km, respectively. Structurally, the sediment-hosted Pb-Zn deposits are generally formed in a specific pattern, in which faults play a major role in controlling this kind of mineralization. Based on this pattern, the first-order, the second-order, and the third-order basins are formed in which, fault confine the second-order basins. Based on the fractal analysis, the distance of these sub-basins was obtained <8, 8-31, and >31 for the third-, the second-, and the first-order basin, respectively. Based on the fractal analysis, it is concluded that deposits in the third-order basin are located about 8Km from each other while the distance between two second-order basins is about 30 Km. Thus, in this research, an exploratory model was proposed based on the results of the fractal method in which the distance between two the second-order basins is about 30 Km. Since the distance between sub-basin numbers 2 and 3 was about 60 Km, there should probably be a second-order basin between them.

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