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Detection of Zones Based on Ore and Gangue Using Fractal and Multivariate Analysis in Chah Gaz Iron Ore Deposit, Central Iran

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Abstract

Detection of mineralized zones based on ores and gangues is important for mine planning and excavation operation. The major goal of this research work was to determine the zones based on ores and gangues by a combination of fractal and factor analysis in the Chah Gaz iron ore (Central Iran). The Concentration-Volume (C-V) fractal method was carried out for Fe, P and S, which indicated that the main mineralized zones consisted of the Fe, S, and P values ≥ 57%, ≤ 0.4%, and ≤0.3%, respectively. Factor analysis categorized variables in two groups including factor 1 (F1) and factor 2 (F2) for ore and gangue, respectively. The C-V fractal modeling on the derived factors showed four zones for F1 and F2. Based on the correlation among the results of fractal modeling on the elements and factors, the first and second zones of F1 were proper for exploitation. Furthermore, the last and first zones of F1 and F2 could be assumed as the main waste for mining excavation.

1. Introduction

One of the main issues for mine planning and design is to provide a proper zoning for a deposit based on ore grades. In addition, detection of zones based on the toxic and harmful elements in different ore deposits is essential for an exploitation operation. Grades of ores and gangue/waste elements are essential for mining exploitation planning, especially for economical calculations [1-7]. Iron ore mines, specifically open-pit mines, as the main source of steel production have produced high amounts of ore minerals among all mining sections [6, 8]. High grades of sulfur and phosphorus in iron ores are harmful in steel industries, health, and environments. Moreover, sulfur weathering in iron ore and waste tailings has produced acid mine drainages (AMDs), which are dangerous for soils, surface waters, and mining equipment [6]. Consequently, high amounts of these harmful elements are negative scores for an extracted block in an iron mine.

Different methods have been introduced and developed for detection of zones in different ore deposits [9]. Mandelbrot (1983) [10] has established fractal modeling for detection of different populations for natural features. Different models have been developed in various branches of geosciences, e.g. concentration-area (C-A) by Cheng *et al.* (1994) [11], concentration-distance (C-D) by Li *et al.* (2003) [12], concentration-volume (C-V) by Afzal *et al.* (2011) [13], and mapping of geochemical indicators by Ghezelbash *et al.* (2019) [14]. The C-V fractal modeling is used to detect mineralized zones in various ores. Furthermore, the C-V model has been utilized for different populations' categorization of other regionalized variables such as rock characteristics, environmental, and economic parameters [4, 6, and 15].

Factor analysis is the main multivariate analysis technique that is utilized for description of exploratory information [16-22]. The basic aim of

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this analysis is to explain the differences in a multivariate dataset by a few groups [16]. Factors can show the mineralization and geochemical processes that generate the correlations among variables [22-25].

The main purpose of this work was to separate different zones based on the iron ore characteristics (Fe%, FeO%, and density of ore), and harmful compounds including sulfur and phosphorus by the factor and C-V fractal modeling in the Chah Gaz iron deposit, Bafq, Central Iran.

2. Methods

2.1. C-V fractal model

Afzal *et al*. (2011) [13] have intended the C–V fractal method, which has been utilized to delineate the threshold values of mineralized zones. The formula is in the following form:

$$V(\geq\rho) \propto \rho^{-D} \quad (1)$$

where ρ and V (≥ ρ) indicate the volumes with concentration values greater than the ρ value and the elemental concentration and D is the fractal dimension. The geochemical data is used after a geostatistical simulation or estimation in this formula [7, 26-28].

2. Factor analysis

The factor analysis is a multivariate analysis method based on the factor analysis for extraction of significant multi-element anomalous signatures. In this approach, to recognize multi-element associations in a geochemical dataset, the non-indicator (noisy) elements are progressively recognized and extracted from the analysis until a satisfactory significant multi-element signature is obtained [16-19]. First, classical PCA was utilized for extracting the common factors. Then the varimax method used for rotation and factors with eigenvalues of > 1 was retained for interpretation [16]. Eigenvalues > 1 are important for determination of optimum of factor number in a factor analysis [16-18]. In addition, the threshold value of 0.3-0.6 for loadings in factor analysis was considered to extract a significant multi-elemental signature of the ore-type sought (Fe in this scenario). These loading values are proper criteria for separation of factors and their components with lower noises in a factor analysis [15, 18-20, and 29].

3. Geological setting

The Chah Gaz iron deposit is located in the Bafq district (central Iran; Figure 1). The Bafq region is situated in an Iranian metallogenic region with different deposits/mines such as Chadormalu (iron and apatite), Koushk (lead and zinc), Esfordi (phosphate-magnetite), and Choghart (iron). Furthermore, there are Precambrian complexes with Ti, V, Mn, Ba, apatite, radioactive elements, Rare Earth Elements (REEs), Pb-Zn massive sulfide deposits, and different Fe ore mineralization types [30-34]. The Chah Gaz deposit is an iron and apatite oxide ore and of the same type as the Gazestan and Zaghia and Lakeh Siah iron ores [35-36]. There is a prominent Fe-oxide–rich core and an overlying body of metasomatite and breccia with hematite and magnetite. The low-grade magnetite-albite ore and, to a lesser extent, magnetite-scapolite ore are widespread. There are high values of sodic alteration and minor calcic alteration zones with iron ores. The post-mineralization alteration zones include silicic, chlorite, sericite, epidote, and carbonation [37].

The influx of Na-rich fluids into the host magmatic rocks leads to deep, relatively extensive sodic, and sodic-calcic alteration, and the formation of albite and scapolite. In the next stage, Ca-rich fluids caused calcic alteration, marked initially by formation of diopside and actinolite, and later, via fluids enriched in iron and phosphorus, the formation of magnetite-apatite ores, with several generations of magnetite-apatite ore formation in the Chah Gaz deposit [37].

4. Discussion

In this work, 3865 core samples of 2-m length were collected from 24 drilled boreholes in this deposit. The collected samples were analyzed by the XRF method for Fe, S, P, and FeO. Furthermore, the density values of ores were measured for 400 samples. The mean and median density values were equal to 4.0706 kg/m^3 and 4.41 kg/m^3, respectively. The statistical results indicate that the Fe, S, P, and FeO mean values are 53.79%, 0.06%, 0.28%, and 17.7119%, respectively (Table 1). Their distributions are not normal (Figure 2). If the median values are assumed to be the threshold values, then the thresholds are 62.39%, 1.139%, 0.829%, and 23.22% for Fe, S, P, and FeO, respectively (Table 1). The elemental 3D models were generated by the ordinary kriging method using the Datamine.Studio.3.21.7164.0 software package (Figure 3).

Table 1. Raw data statistical parameters.

Statistical parameter	Fe (%)	S (%)	P (%)	FeO (%)	Density (Kg/m^3)
Mean	53.79	0.60	0.28	17.71	4.07
Median	55.44	0.43	0.12	17.59	4.11
SD	8.601	0.53	0.54	5.511	0.33
SV	73.98	0.29	0.29	30.37	0.11
Maximum	72.81	3.26	6.57	28.60	4.73
Minimum	22.04	0.04	0.00	0.00	2.68

SD: standard deviation; SV: sample variance.

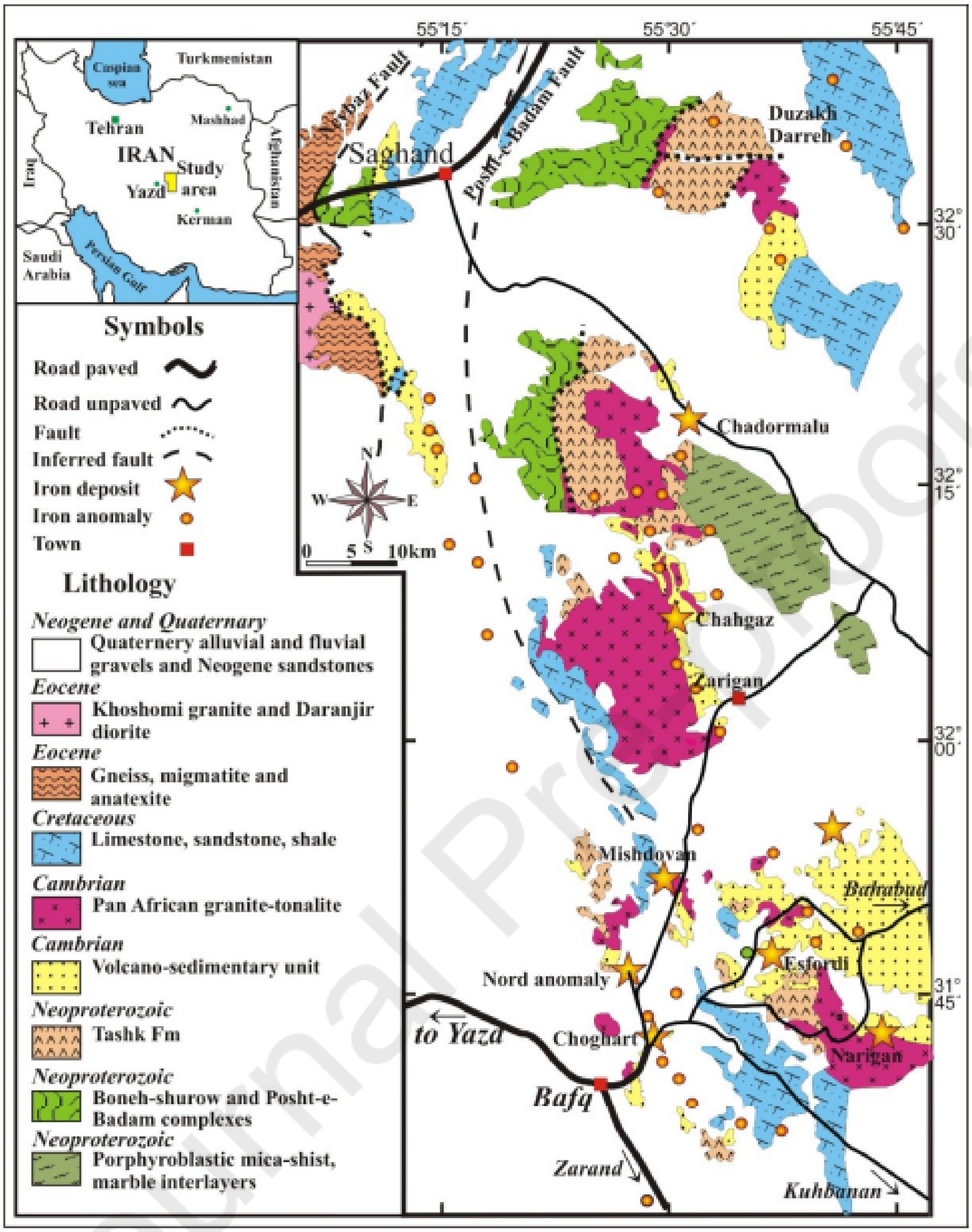

Figure 1. Chah Gaz deposit (red rectangle) and other iron ore locations in the Bafq region [37].

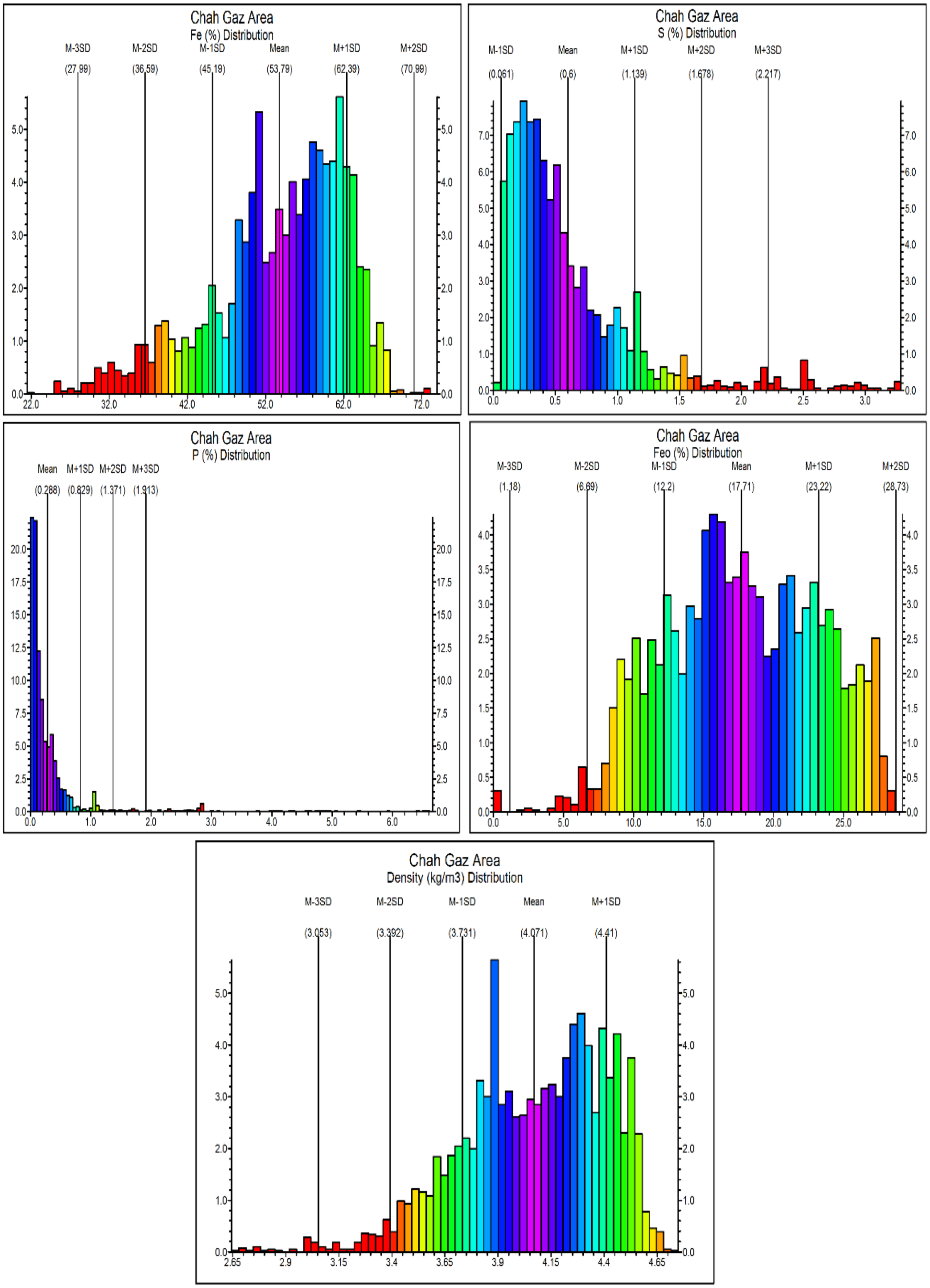

Figure 2. The Fe, S, P, FeO, and density histograms.

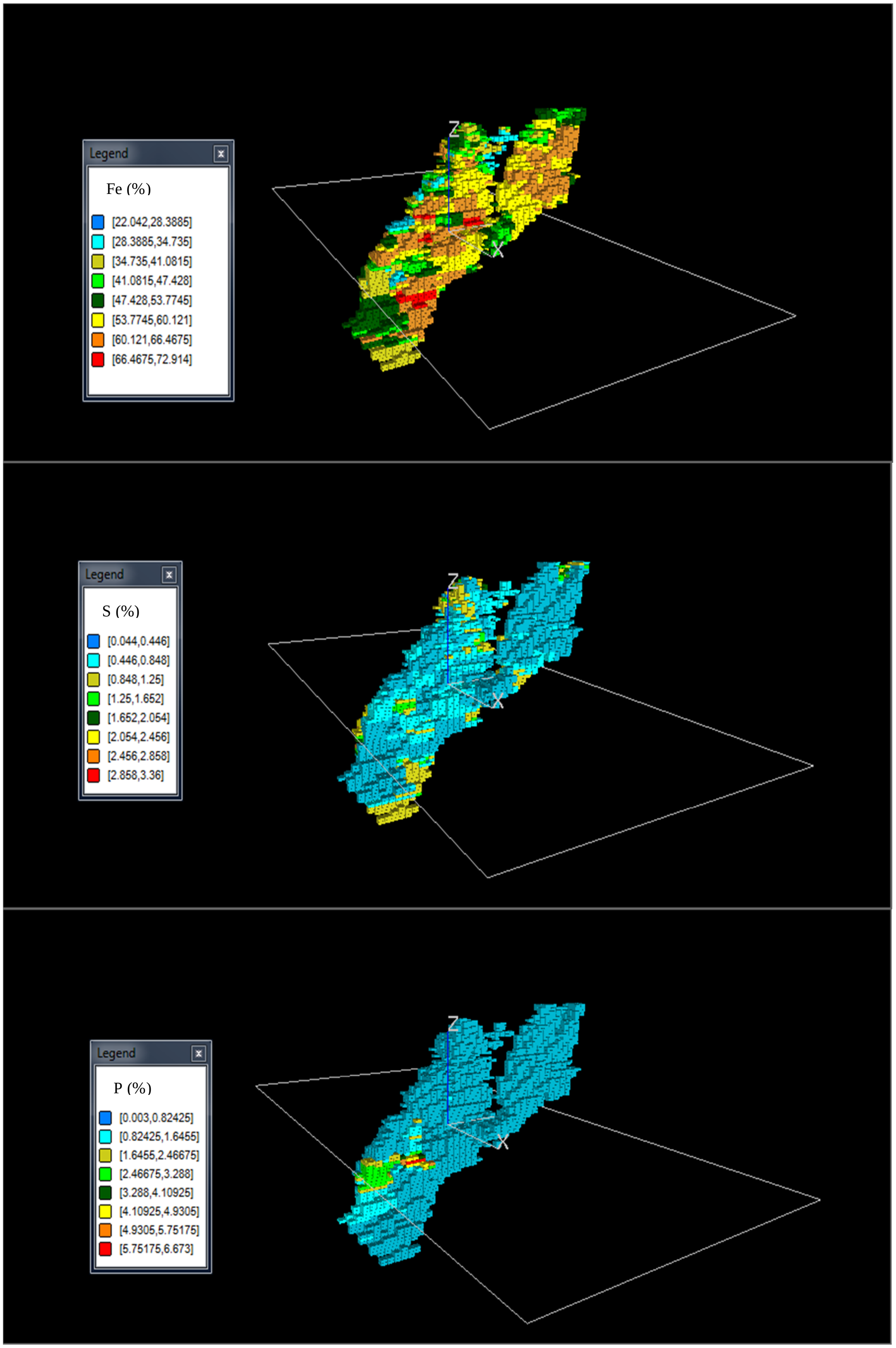

Figure 3. The Fe, S, P, FeO, and density distribution maps of the Chah Gaz deposit.

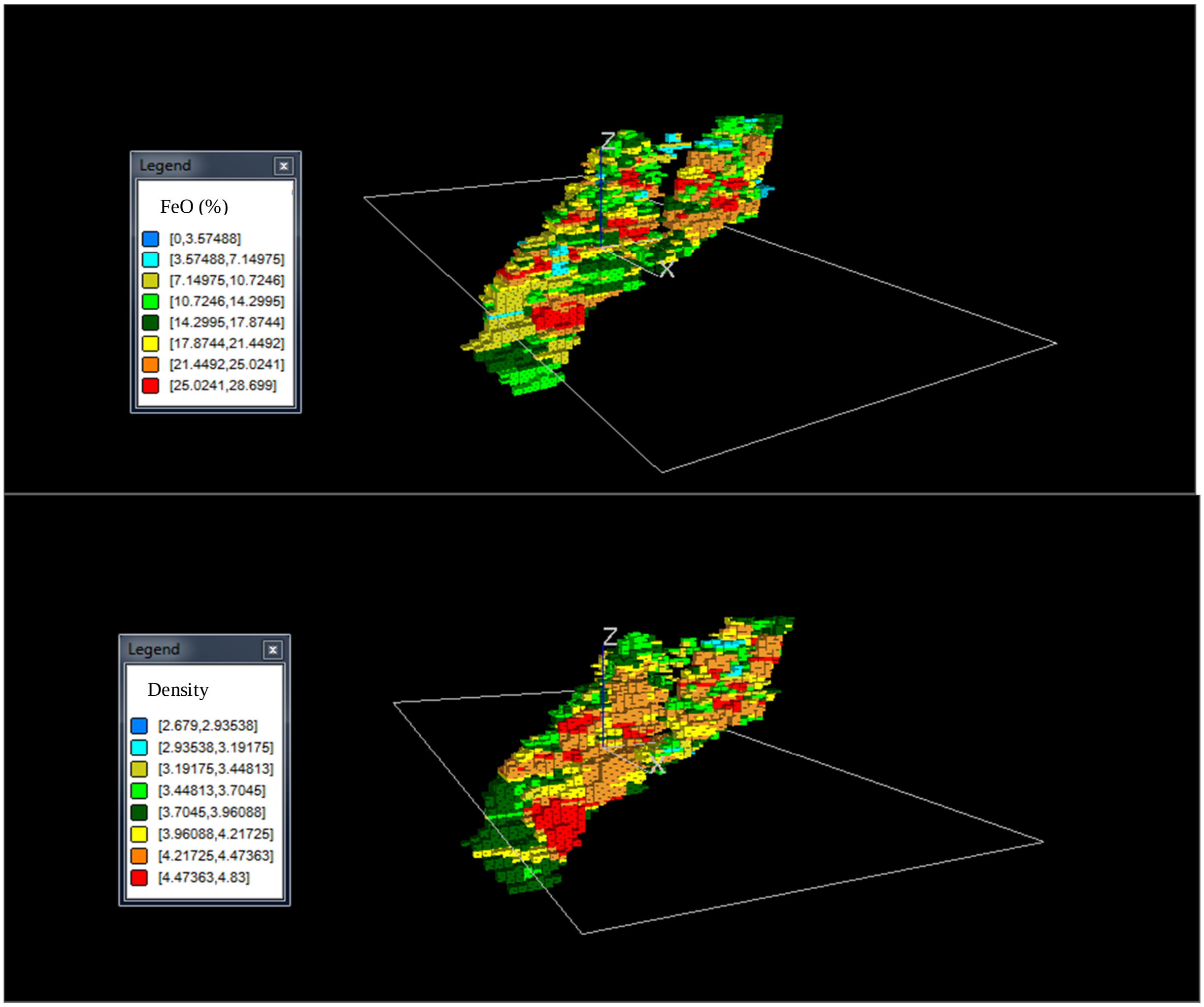

Figure 3. Continuation

4.1. Application of factor analysis in Chah Gaz deposit

The factor analysis was used for extraction of factors based on the Fe, FeO, S, P, and density data, and also the varimax rotation of factors was applied using the SPSS software. Moreover, the factor analysis generated two rotated components with eigenvalues greater than 1 (Table 2):

(1) Fe, FeO, and density;

(2) S and P.

The first group that is important for mineralization includes the Fe and ore parameters without gangues. The factor plots in rotated space are indicated for a better presentation of the extracted factors (Figure 4). The second factor represents the gangue minerals for sulfur and phosphorus.

4.2. Application of C-V fractal model

The C-V log–log plots were created for Fe, FeO, S, P, and density based on the sub-surface data (Figure 5). The beak points of the straight-line segments in the log–log plots indicate the threshold values discriminating the concentration volume populations, which demonstrate the geological differences. Based on these log-log plots, there are three populations for density and five populations for Fe, S, P, and FeO (Figure 5). The Fe threshold of the main mineralized zone was about 57% (Figure 5). Moreover, a major Fe enrichment zone occurred at 67.6073%. In addition, the first and extreme S thresholds for the sulfidic zone were 0.1513 and 2.1135 %, respectively. The first and last P thresholds were 0.0456% and 2.9512 %, respectively; the P enrichment commences at 2.9512% (Figure 5). The backgrounds of S and P were lower than 0.4% and 0.3%, respectively. The first and high intensity mineralized thresholds for FeO were 3.57488% and 25.0241%, respectively. Moreover, the first and highly intensity thresholds for density were 3.6307 and 4.2658 kg/m^3, respectively, as depicted in Figure 5.

Table 2. Rotated component matrix in one step: loadings in bold show the selected factors with the threshold of 0.6.

	Component A	
Elements	F1	F2
Fe	**.890**	.088
S	-.328	**-.665**
P	-.258	**.782**
FeO	**.844**	-.199
Density	**.873**	.131
Eigen-value	2.440	1.119
Variance (%)	48.807	22.388
Cumulative variance (%)	48.807	71.195

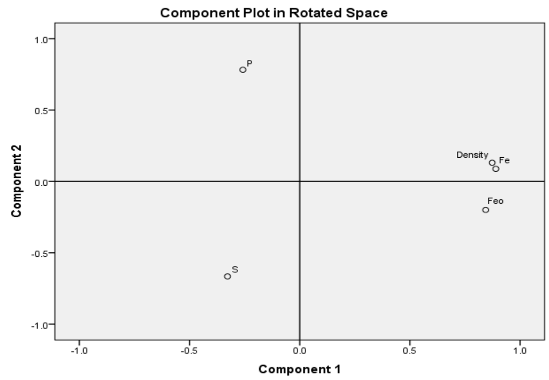

Figure 4. Component plot in rotated space.

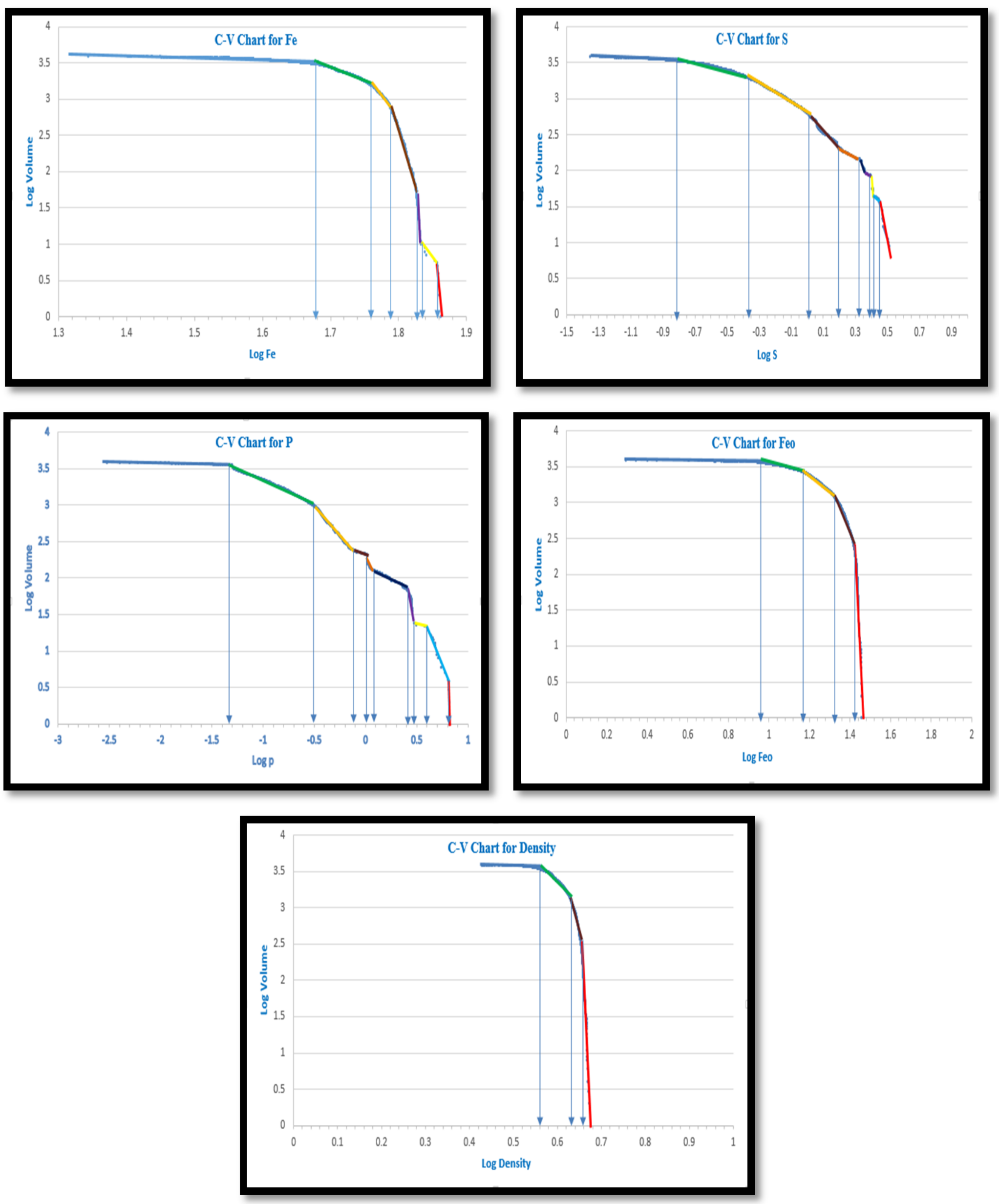

Figure 5. C–V Log–log plots for Fe, S, P, FeO, and density.

Based on the fractal modeling results, the F1 and F2 distribution 3D models were built up, as depicted in Figure 6. The main mineralized zone of Fe includes 22 blocks in the Chah Gaz deposit. The major zones of S, P, FeO, and density included 145, 126, 253, and 1366 blocks in this deposit, respectively (Figure 6).
Additionally, the C-V log–log graphs were produced for F1 and F2, which had a multi-fractal nature, as shown in Figure 7. Factor populations are demonstrated in these log–log plots, and also there are four populations for both of them, depicted in Figure 7. The F1 first and high intensive thresholds of mineralized zones were 0.16981 and 1.02, respectively, which indicateed that a major F1 enrichment zone occurred at 1.02. Furthermore, a highly F2 threshold for the main mineralized zone commenced from 1.90548, as depicted in Figure 7. The main mineralized zones of F1 (Fe, FeO, and density) consist of 716 blocks in the deposit. However, high-intensity zones of F2 (S and P) include 101 blocks in the Chah Gaz deposit, as depicted in Figure 8.

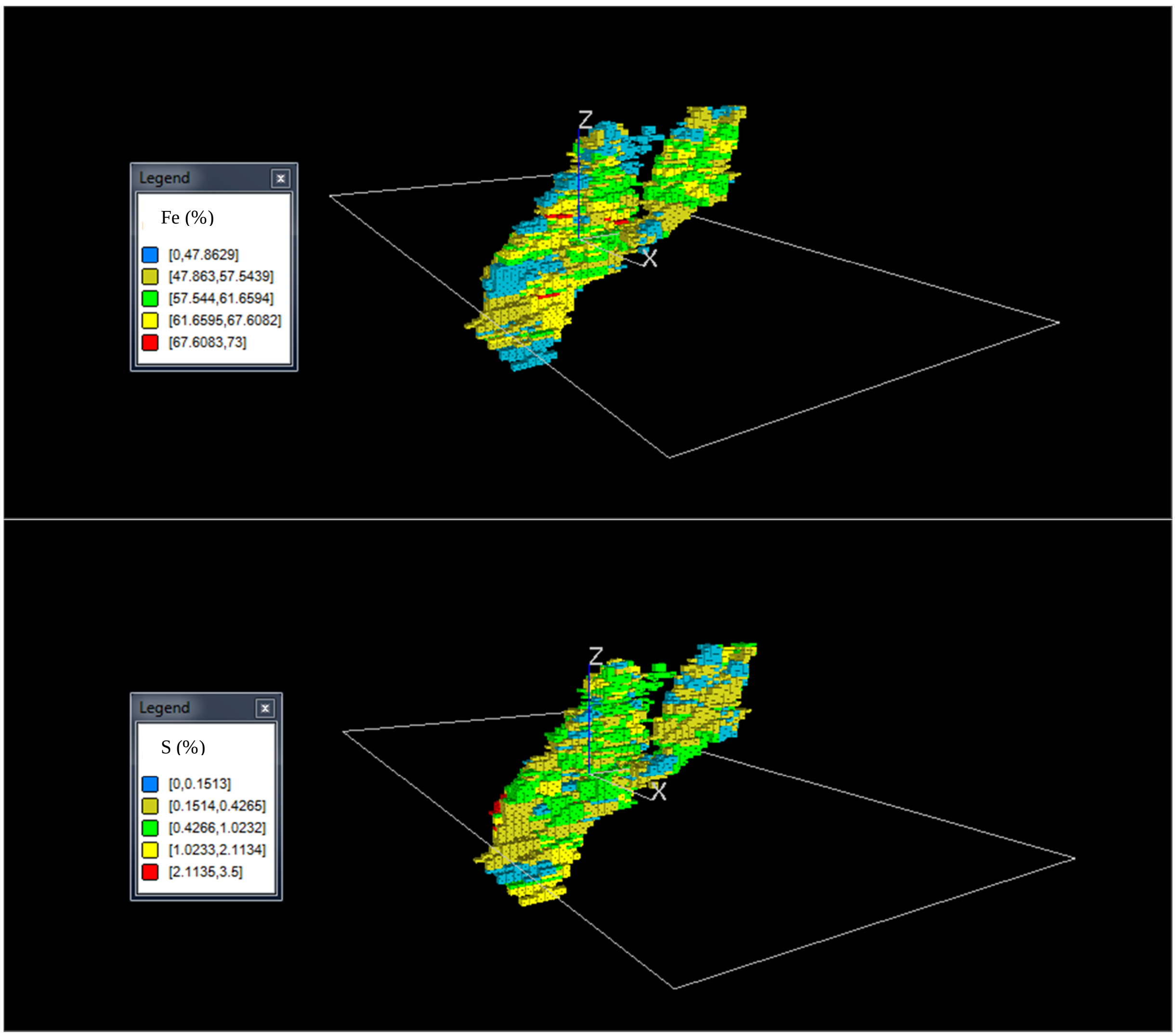

Figure 6. Fe, S, P, FeO, and density population distribution models due to the C–V method.

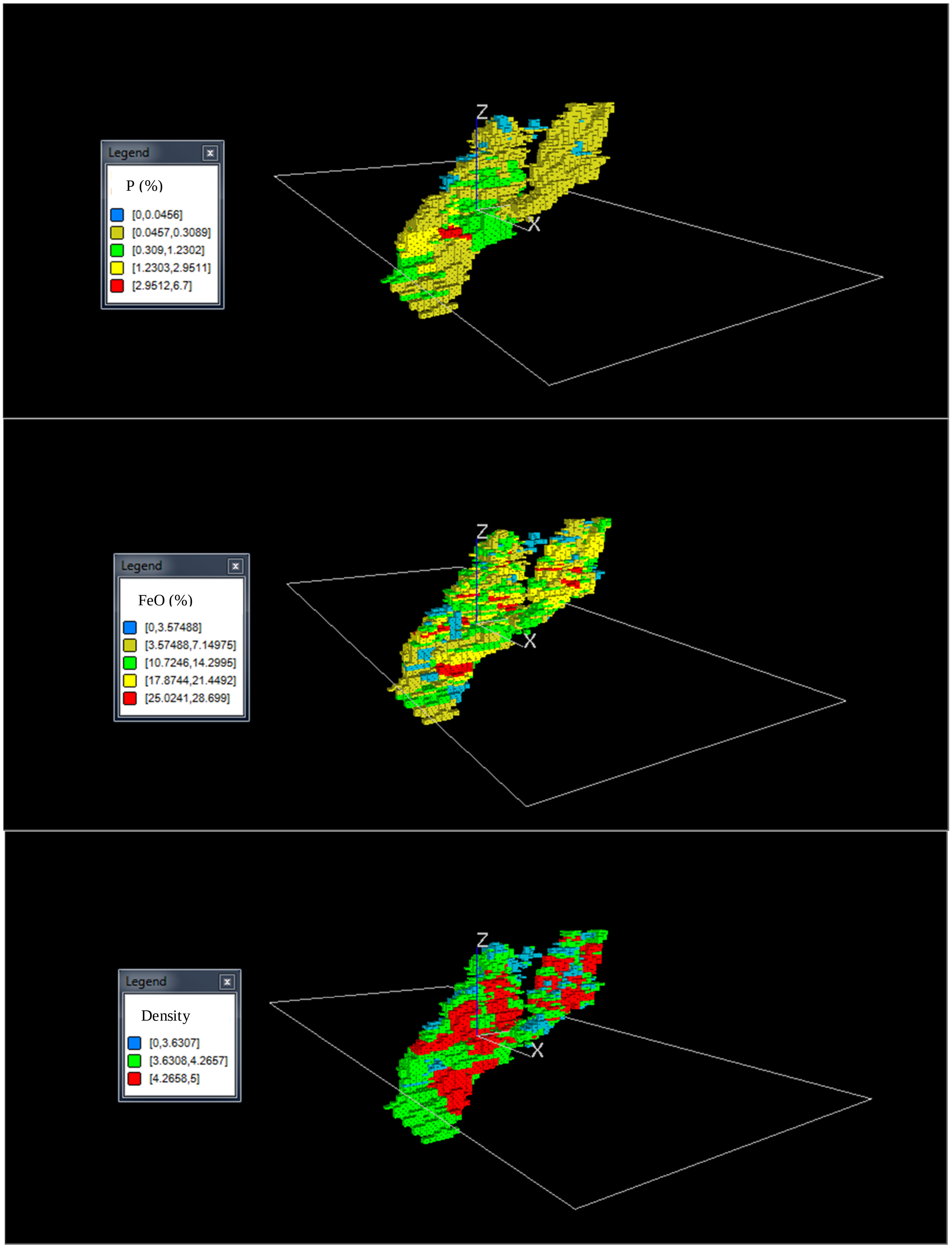

Figure 6. Continuation

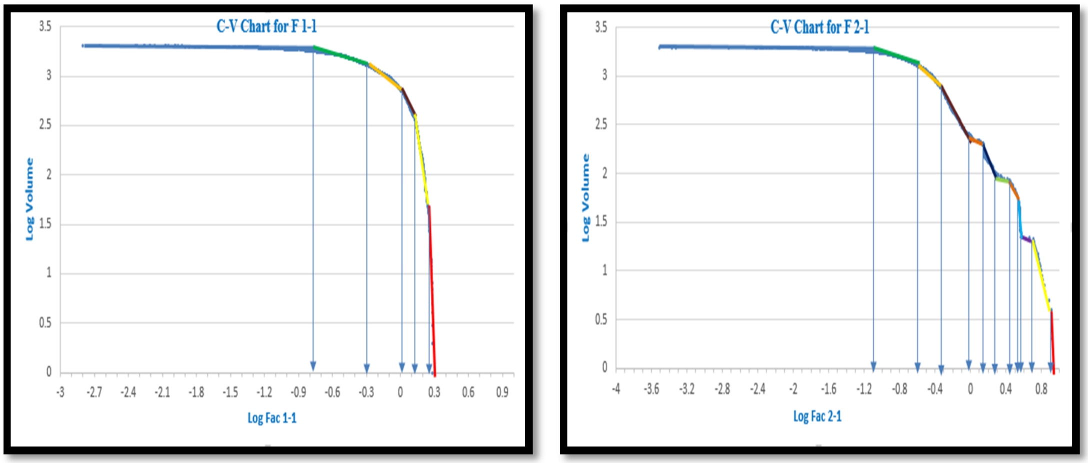

Figure 7. C–V log–log diagrams for F1 and F2.

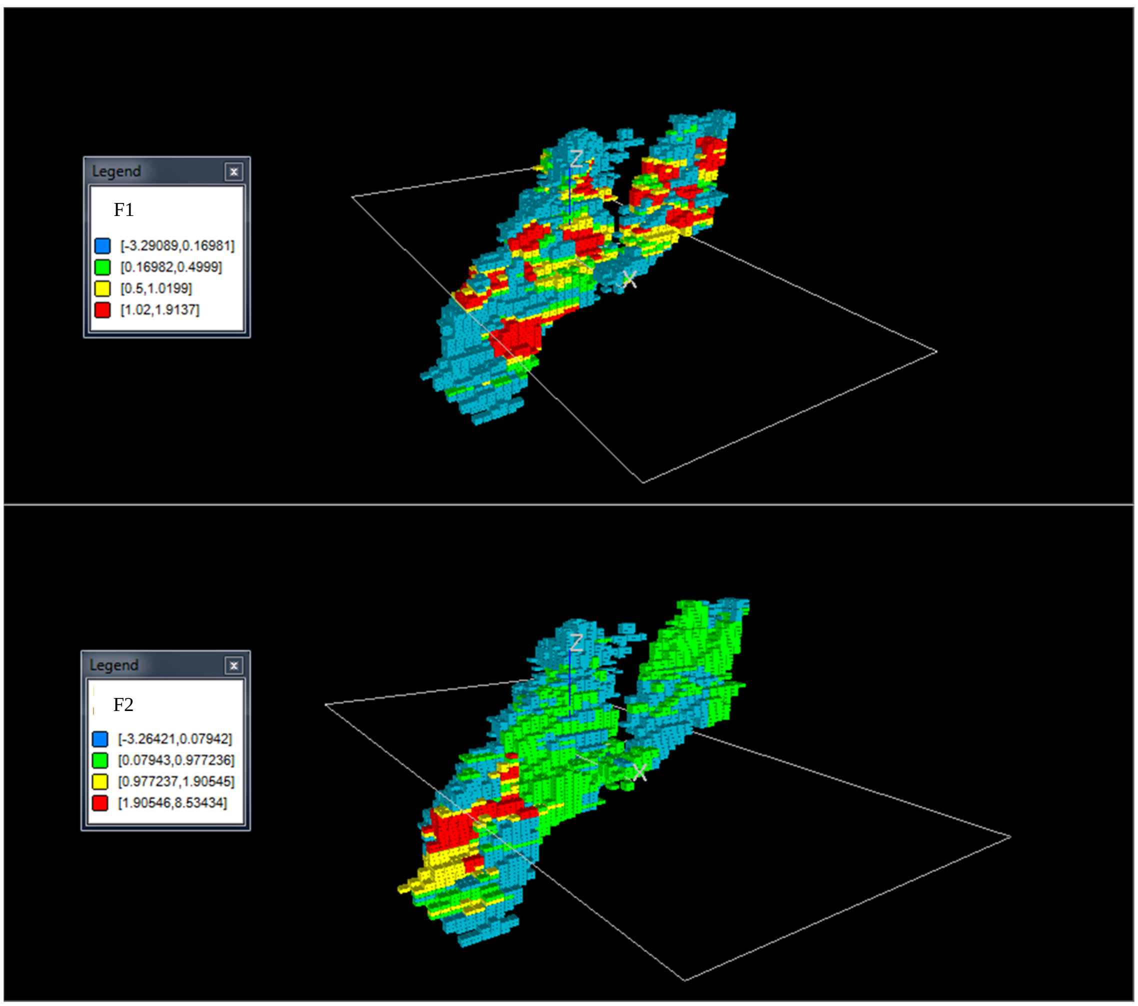

Figure 8. F1 and F2 3D models on the basis of C–V process.

4.3. Correlation between mono/multivariate fractal modeling

In this section, a comparison was carried out between the factor zones, the statistical parameters, and the C-V models of all variables (Tables 3 and 4). These statistical parameters were the mean, maximum, and minimum of Fe, FeO, S, P, and density. Zones of factor 1 can reveal the ore zones of this deposit for mine planning. The first zone of F1 (> 1.02) can be the main zone for exploitation, which contains the high-grade Fe mineralized zone and low-grade sulfur and phosphorous zones, as depicted in Table 3. The averages of Fe, S, and P were 63%, 0.4%, and 0.18%, respectively. This zone was correlated with the main zones of Fe and background populations of S and P according to the C-V fractal modeling. The second zone of F1 had factor scores between 0.5 and 1.02, which could be determined as a mineable zone based on the ore and gangue grades. The Fe, S, and P means were 59%, 0.46%, and 0.2%, respectively. The iron ore grades were proper in this zone but the gangue values were higher than the first zone (Table 3). The third (0.17-0.5) zone of F1 had a suitable Fe content (Fe average was 57%) but this zone contained high values of P and S with means of 0.25% and 0.47%, as depicted in Table 3. Finally, the F1 fourth or last zone consists of background zones for Fe and high-intensive zones for S and P. Consequently, the average values for Fe, P, and S were 48%, 0.35%, and 0.73%, respectively. On the other hand, the third and fourth zones were not a priority for exploitation.

Table 3. F1 (Fe, FeO, and density) zones obtained by the C-V fractal analysis in comparison with the statistical parameters of Fe, S, and P.

Block No.	Mean P (%)	Mean S (%)	Mean Fe (%)	P (%)		S (%)		Fe (%)		F1		Zone name
				Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	
716	0.186	0.4	63.35	0.024	0.748	0.056	1.5	57.27	72.81	1.02	1.9137	1
585	0.2	0.46	59.38	0.004	1.14	0.061	1.58	52.5	66.277	0.5	1.019	2
489	0.247	0.474	57.07	0.004	1.625	0.052	1.627	48.40	67.02	0.16982	0.4999	3
2075	0.35	0.73	48.14	0.003	6.573	0.044	3.26	22.042	65.20	-3.29	0.16981	4

The F2 zones could be shown as the gangue zones of this deposit for mine planning and design. The first zone of F2 (> 1.9) could be assumed as the main waste zone that contained low Fe grade (Fe average ≈ 42%) and high-grade sulfur and phosphorous zones with averages of 0.45% and 3.01%, respectively, as depicted in Table 4. Averages of Fe, S, and P were 63%, 0.4%, and 0.18%, respectively. This zone was correlated with the main zones of S and P and background populations of Fe based on the C-V fractal modeling. The main mineralized zones for Fe with low values of S and P was the fourth zone. The mean values for Fe, S, and P were equal to 56.3%, 0.086%, and 0.11%, respectively. Furthermore, the third zone contained proper values of Fe, S, and P based on mining excavation. Averages of Fe, S, and P were 56%, 0.28%, and 0.23%, respectively (Table 4). On the other hand, the third and fourth zones of F2 were a priority for exploitation, and these were correlated with the first and second zones of F1.

Table 4. F1 (S and P) zones obtained by the C-V fractal analysis in comparison with the statistical parameters of Fe, S, and P.

Block No.	Mean P (%)	Mean S (%)	Mean Fe (%)	P (%)		S (%)		Fe (%)		F2		Zone name
				Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	
101	3.01	0.45	42.19	1.101	6.573	0.131	1.642	26.364	67.02	1.905460	8.53434	1
145	1.06	0.35	51.05	0.55	1.953	0.07	1.563	28.739	64.35	0.977237	1.90545	2
1539	0.236	0.278	56.81	0.011	1.028	0.044	1.532	22.04	72.81	0.07943	0.97502	3
2080	0.11	0.086	56.3	0.003	1.079	0.057	3.26	25.22	68.111	-3.26421	0.07942	4

5. Conclusions

Utilizing both the C-V fractal and factor analysis could improve explanation of the sub-surface data in a detailed exploration. The results obtained from this work show that a combination of the factor analysis and fractal modeling is a suitable methodology for determination of the proper zones for planning the exploitation. This method is based on the ore and gangue minerals simultaneously. The factor analysis separated the ore and gangue variables into two groups. However, the main mineralized zones contained Fe ≥ 57%, S ≤ 0.4%, and P ≤ 0.3%, which were correlated with the first and second zones of F1 as the ore factor. The major waste populations were the first and fourth zones of F2 and F1, respectively. Consequently, this methodology could be used for other iron ores in the Bafq region and other countries with similar mineralization characteristics.

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جدایش زون‌ها با استفاده از مدلسازی فرکتالی چندمتغیره براساس کانه و باطله زمین‌شناسی در کانسار سنگ آهن چاه‌گز، ایران مرکزی

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چکیده:

جدایش زون‌های کانه‌زایی براساس کانه و باطله زمین‌شناختی امری ضروری جهت طراحی و بهره‌برداری از یک معدن است. هدف اصلی این پژوهش جدایش این زون‌ها برپایه کانه و باطله و با استفاده از ترکیب دو روش آنالیز آماری چندمتغیره و نیز مدلسازی فرکتالی به روش عیار-حجم در کانسار سنگ آهن چاه‌گز واقع در بافق و زون ایران مرکزی است. براساس مدلسازی فرکتالی عیار-حجم زون اصلی کانه‌زایی شامل عیار آهن بیش از 57 درصد و نیز فسفر و گوگرد به ترتیب دارای عیارهای کمتر از 0/4 و 0/3 درصد هستند. همچنین نتایج حاصل از آنالیز فاکتوری نتایج حاصل از کانه و باطله را در دو فاکتور جداگانه قرار داد. فاکتور یکم مربوط به کانه و فاکتور دوم مربوط به باطله است. مدلسازی فرکتالی بر روی دو فاکتور برای هر یک چهار جامعه را نشان داد. براساس مقایسه این جوامع با عیار میانگین عناصر در آنها، بهترین جوامع جهت برنامه‌ریزی استخراجی را در فاکتور کانه می‌توان جوامع یکم و دوم در نظر گرفت. همچنین جوامع یکم و آخر به ترتیب برای فاکتورهای باطله و کانه را می‌توان بعنوان باطله معدنی درنظر گرفت.

کلمات کلیدی: کانه، باطله زمین‌شناسی، مدل فرکتالی عیار-حجم، آنالیز فاکتوری، چاه‌گز.