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Research Paper

Combining Sequential Gaussian Simulation and Fractal Analysis for Mapping of Cu Concentration in Haftcheshmeh Porphyry Copper Deposit

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Abstract

In this paper a hybrid approach of Sequential Gaussian Simulation (SGSIM) and Concentration-Volume (C-V) fractal method was applied to boreholes data for classification of major geochemical parameters and associated features with alteration zones of the Haftcheshmeh Cu deposit in NW of Iran. Thereupon, Cu parameters were detected with higher efficiency and lower uncertainty. The purpose is also extended to delineate the alteration zones pertinent to Cu mineralization. Firstly, the most straightforward simulation (SGSIM) was utilized for projecting different lithogeochemical parameters of Cu. Then the C-V fractal model was used to discriminate these parameters by thresholds, obtained from the C-V Log-Log plot. The Fractal based resulting maps of 10 realizations and their E-type indicate their association with potassic alteration that has imposed on porphyry granodiorite. Moreover, these maps illustrate that the boreholes (1, 9, 23, and 31) at about longitudes of 643400 to 643800 are more promising than others. This fact explicitly had been correlated with reality of the studied area and denoted in its primary surface map. The results based on SGSIM, C-V confirmed enhanced mineralization in three-dimensional maps of the Haftcheshmeh deposit as a powerful combined method that can be used to detect the similar ore zones in continuation of the ore roots in adjacent areas.

Keywords

Sequential Gaussian Simulation, (C-V) Fractal, Cu geochemical potential mapping, Alterations, Haftcheshmeh, Iran.

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1- INTRODUCTION

In most of the geochemical exploration programs a well-established model in a specific promising zone can be successfully used in adjoining areas to extent mineralization zones. In this respect, sufficiently conventional geostatistical methods to distinguish precise geochemical parameters are essential, which are applied for characterizing spatial variability of elements with their specific limitations. Kriging is considered as a powerful estimator in this regard but often causes smoothing effects due to higher skewness in a set of mineralized data, resulting in reduction of variation of different elements. Therefore, it is incapable of detecting and reducing uncertainties related to mineralization. To overcome this hindrance, conditional stochastic simulation suggested by [1,2] was implemented. Initially, conditional sequential Gaussian simulation (SGSIM) was used for obtaining an overview model of spatial distribution and variability of boreholes data in the Haftcheshmeh area. The SGSIM generates certain histograms and semi-variograms that refer to the sample data at their original locations. Therefore, the resulting map represents a more realistic spatial distribution of an attribute than the kriged one [3-5]. In this regard, initially Cu values are modeled by SGSIM. In the next step, Concentration-Volume (C-V) Fractal method was used to discriminate different lithogeochemical thresholds of Cu. A variety of fractal/multifractal models have been applied based on the characteristic of geochemical data and purpose of usage, such as Concentration-Area (C-A) fractal [6]; the Number-Size model (N-S) [7], Spectrum- Area (S-A) [8], Concentration-Distance model (C-D) [9], singularity index [10], and Concentration-Volume model (C-V) [11] and their comparison by various authors [12-15].

In order to perform the ultimate goal, different single and fused methods were assessed. In Recent decades, fused methods successfully reduced uncertainty of detected mineralized zones and suggested by many authors [16,17]. Here, integration of SGSIM and C-V fractal model was used as a powerful tool for differentiating geochemical populations of Cu concentrations in the hypogene zone of the Haftcheshmeh porphyry deposit. This hybrid method showed more trustworthy outcomes than a single traditional method in detecting ore zones that are completely corresponding to the major alteration of the area (potassic zone). Figure 1 illustrates concise techniques used in each step of this study.

2- GEOLOGY AND METALLOGENY OF THE AREA

Haftchemeh with *Cu+Mo±Au* porphyry mineralization is located in a volcanic–intrusive complex of Urmieh-Dokhtar Magmatic Arc (UDMA) and Arasbaran Cu mineralization zone at about 135 Km of the Tabriz city in NW of Iran. In Oligocene, gabbro massive, emplaced in Cretaceous-Paleocene pyroclastic volcanic units. Then diorite massive intruded to gabbro (early Miocene). In the final steps another massive with granodioritic and mineral-bearing felsic intrusive rocks penetrated to the former settings. In most of the porphyry Cu deposits, mineralization massive usually injects into older volcanic rocks, but in this deposit, granodioritic intrusive massive intruded to another intrusive rock with basic and gabbro composition [18]. All of the mentioned intrusive rocks were cut by several dikes with mixtures of andesite to diorite. Figure 2 shows the distribution of various lithologies along with prevailing alterations (potassic, phyllic and propylitic) in the study area. Here intrusive porphyry diorite strongly has been altered and contains frequent silicified veinlets with small occurrence of *Cu±Mo* mineralization in the west of the area. Another intrusive unit with the same mineralization is porphyry granodiorite, which has been influenced by potassic and phyllic alterations. This intrusive unit probably has genetic relationship with intrusive rocks of granite and diorite; therefore, it can be described as a postponed phase. All in all, the magmatic evolution of this area includes several sequences of intruding different intrusive units from gabbro to granodiorite and then variety of dikes. Figure 3 illustrates a clear contact between intrusive granodiorite with potassic alteration (bright color) and diorite (dark color) in the area. Dikes networks are dense and elongated from NW to SE with gabbro and granodiorite settings.

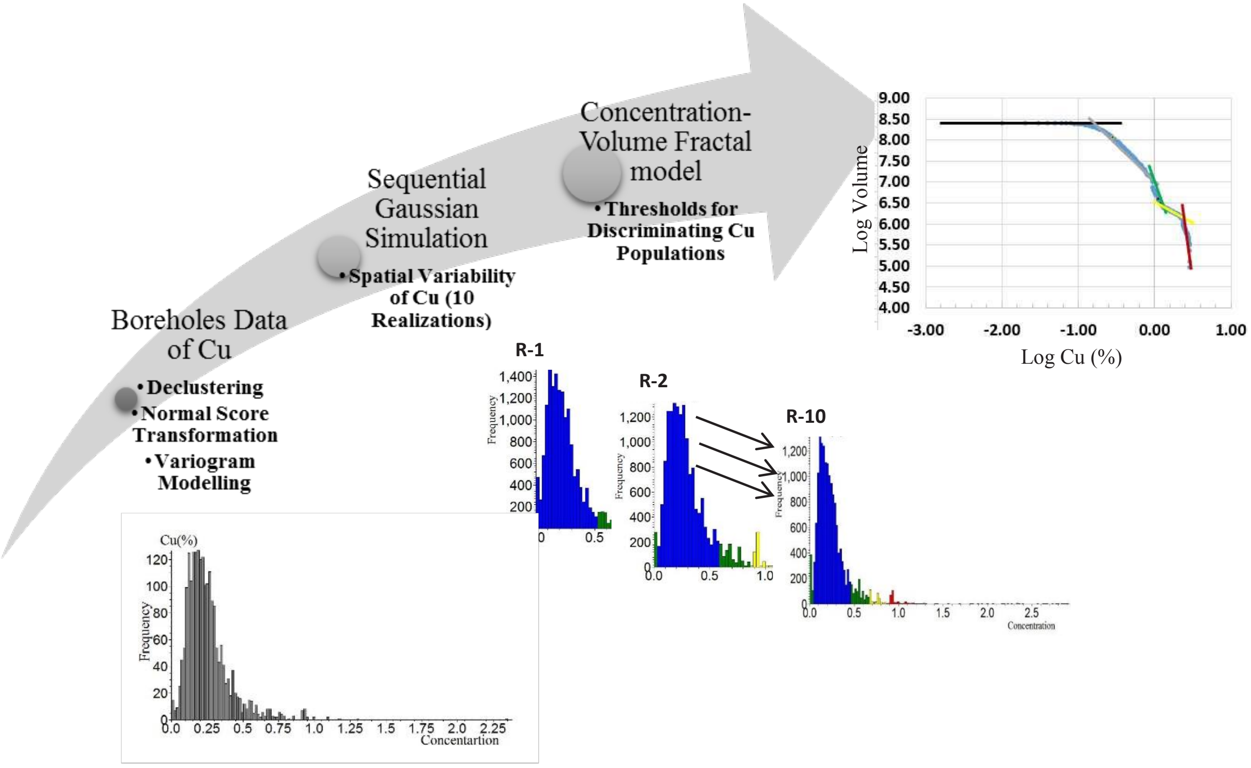


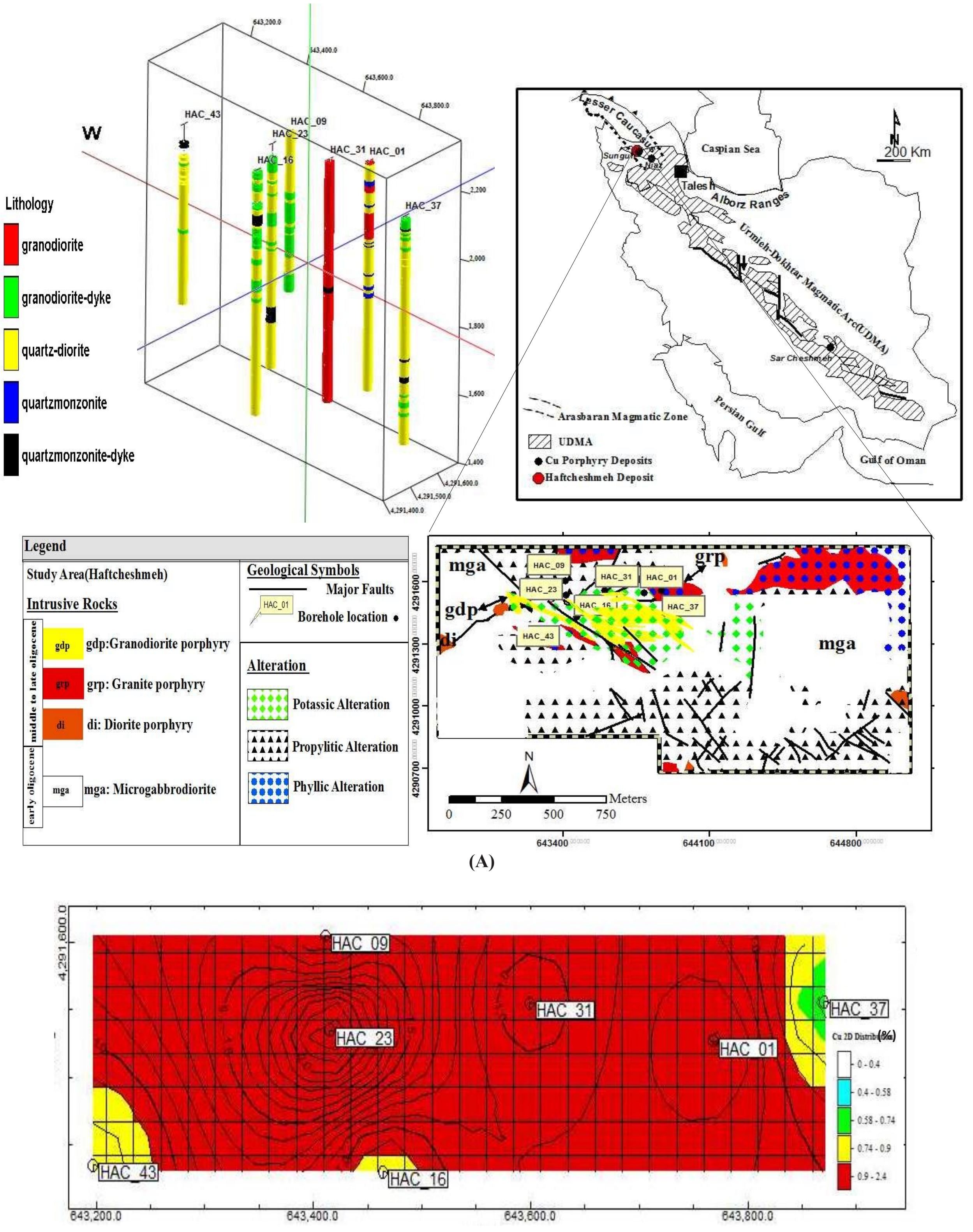
Figure 1. Block diagram of the proposed method

Based on the executed drilling and objectives of this paper, seven boreholes were selected (Figure 2). It was clearly observed that, potassic alteration accompanies mainly with Cu-mineralization along these boreholes and continues to the depth of 700m. The boreholes study suggests a variation in composition of igneous body from gabbro diorite, quartzdiorite, quartzmonzonite to granodiorite (Figure 4). Porphyry granite is affected by phyllic alteration and gradually transformed from potassic to phyllic. In phyllic zone quartz, sericite and pyrite are the dominant primary minerals. The major part of mineralization is confined to the potassic zone and to some extent the phyllic zone of the area which is encompassed by propylitic alterations. Cu mineralization mainly has occurred in gabbro (intrusive rock) and granodiorite (host rock) as dispersed and vein-veinlet forms. A preliminary assessment suggests an average grade of 0.5% Cu with 300 ppm Mo for Haftcheshmeh deposit, indicating lower Cu and higher Mo compared to Sungun deposit.

3- METHODOLOGY

3-1- Sequential Gaussian conditional simulation (SGSIM)

Sequential Gaussian simulation (SGSIM) is one of the most useful methods for simulation of geochemical data because of its simplicity and feasibility particularly, while applying to borehole data. SGSIM is a broadly known algorithm and executable in many mining software tools. The method is established on a multi-Gaussian random function (RF) model which provides joint realizations of the component from (RF) model. Sequential principle is used for generating realizations of a multivariate Gaussian field. A simulated value at a visited point is randomly drawn from the conditional cumulative distribution function (CCDF), defined by simple kriging (SK). All original and formerly simulated values as the conditioning data situated in proximity of the location being simulated. In order to execute SGSIM, at first, the data z(u) was transformed into normal score space Y(u). If Y(u) is a multivariate Gaussian and RF with zero mean, unit variance



(A)

(B)

Figure 2. A: Simplified geological map of the study area, three-dimensional section and lithology of the boreholes, B: Surface map of Cu lithogeochemical populations

(A) (B)

Figure 3. A: Overall view showing contact between intrusive granodiorite (bright color) and diorite (dark color), B: close up view of granodiorite porphyry unit [19]

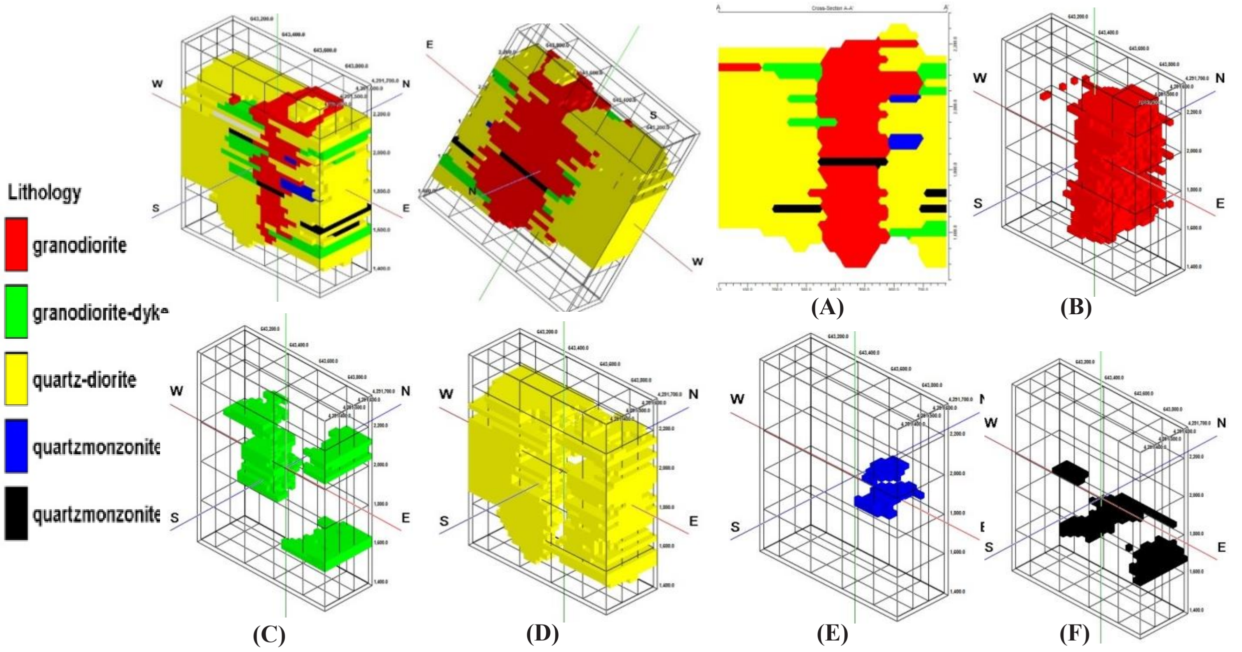


Figure 4. General lithological units of seven boreholes of the Haftcheshmeh; A: cross-section along A-A′, B: granodiorite, C: granodiorite-dyke, D: quartz-diorite, E: quartzmonzonite, F: quartzmonzonite –dyke

and given variogram model $\gamma(h)$, then realizations of Y(u) can be generated by this algorithm [20-22]. Afterwards, the Gaussian simulated field was back transformed into the data space. Different steps adopted for generating SGSIM maps are outlined in the flowchart shown in Figure 5.

3-2- Concentration-volume (C-V) fractal model

Fractals are mostly used for differentiating lithogeochemical parameters by thresholds obtained from the Log-Log plot. Unlike unstructured conventional methods, fractals are needless to manipulate data. So that they are easily applied for the wide ranges of data in recent researches. In this paper, the Concentration-volume (C-V) fractal model was utilized for obtaining different Cu populations along boreholes. The C-V fractal model is defined as [11]:

$$V(\rho \le \upsilon) \propto \rho^{-a_1}; V(\rho \ge \upsilon) \propto \rho^{-a_2} \quad (1)$$

Where:

$V(\rho \ge \upsilon)$: indicates the volume with concentration value less than or equal to contour value ρ,

$V(\rho \le \upsilon)$: indicates the volume with concentration value greater than or equal to the contour value ρ,

υ: shows the threshold value of a geological zone (or volume),

a_1 and a_2: are the characteristic exponent [11].

4- RESULTS AND DISCUSSION

4-1- Application of SGSIM

In this research, the (SGEMS) software was used to execute SGSIM. A regular 3-D grid with 25×25×25 m^3 block support was utilized for this study. Figure 6 indicates Cu raw values and 10 simulated realizations histograms. At first, delustering was applied to boreholes data and then Cu distribution transformed into Gaussian one by using normal scores transformation. Thereby, 10 realizations were produced. Figure 7 illustrates realistic spatial distribution of Cu by 10 realizations. In order to validate the outputs of the algorithm, the variograms parameters for simulated Cu were compared with the original one, where satisfactory yield was observed (Figure 8). Totally 2102 borehole samples from the hypogene zone of the Haftcheshmeh were simulated by SGSIM and their statistics are presented in Table 1.

Simulation was performed using the simple kriging estimator. All of the realizations have proximate results. These realizations are employed by the fractal model where each realization represents a realistic spatial distribution of Cu without a smoothing effect. The CDFS of all realizations and E-Type are displayed in Figure 9 which reveals that the sample histogram reproduced by realizations is quite acceptable. Likewise, the reproductions of raw data semi-variogram models by selected realizations are also acceptable and optimized (Figure 8 and Table 2). According to [22] some differences were seen between various realizations and sample models, are acceptable which may have various causes such as type of algorithm, the semi-variogram model parameters and the quantity of conditioning data applied to the simulation (Table 2).

4-2- Application of C-V Fractal model

In this study, the borehole data of ore concentrations were calculated by (SGSIM), where $V(\rho \le \upsilon)$ and $V(\rho \ge \upsilon)$ are volumes surrounded by a contour level ρ in a 3D model. Overall, 10 simulated realizations of Cu and E-Type were used in the fractal model which detected different Cu mineralization zones along boreholes. At first, these realizations back transformed into the original unit and according to voxel size of 25×25×25 m^3, volumes corresponding to different Cu values were calculated to obtain the C-V fractal model. Figure 10 depicts C-V Log-Log plots of different Cu realizations from which different threshold values of Cu were acquired (Table 3). Accordingly, the distribution maps of Cu along seven boreholes of the Haftcheshmeh deposit were prepared (Figure 11).

Meanwhile, certain anomalies of 10 realizations demonstrated in Figure 12 clearly show that most of the Cu mineralization zones are confined to

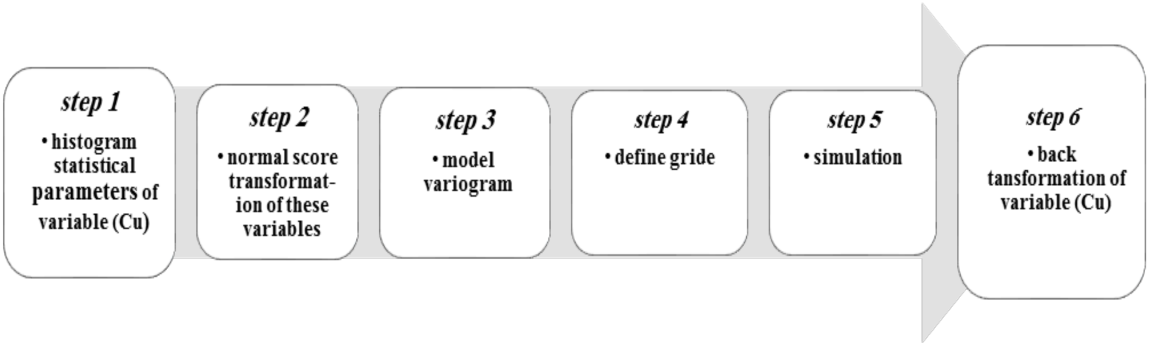


Figure 5. Flowchart showing outline of different steps attempted for generating SGSIM map

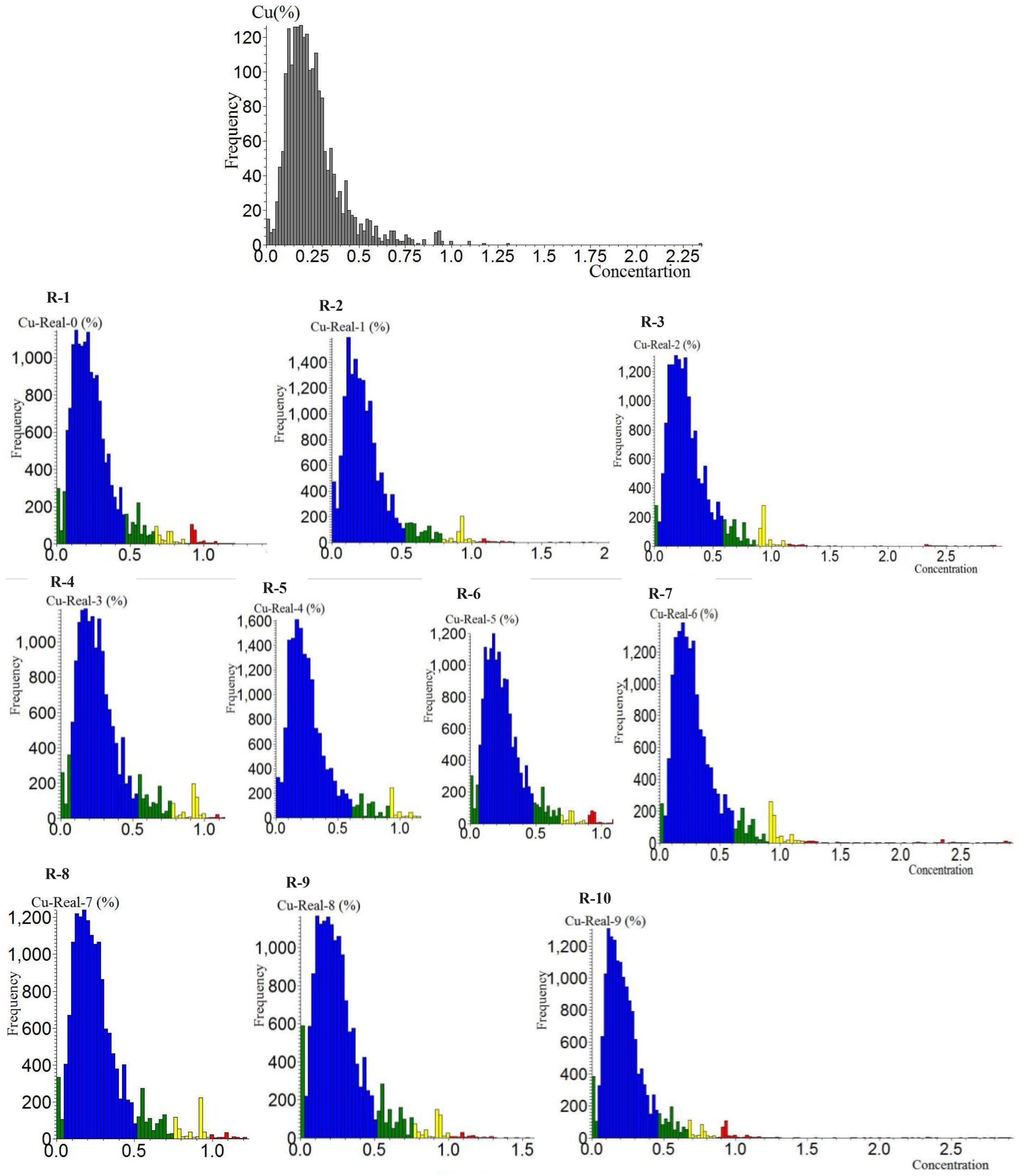


Figure 6. Histograms of Cu for boreholes raw data and 10 simulated realizations (R=Realization)

lower levels of the sections, concentrated in the east and NE-SW part of the area. The fact is clearly emphasized by the highest concentration of Cu in R-5, 6 and 7 of Figure 12.

The major ore bearing potassic and phyllic alterations in the area were also distinguished by the inverse distance weighted interpolation method (Figure 13). The figures revealed that the phyllic alteration has been converted to potassic at lower levels of the area and uncertainties

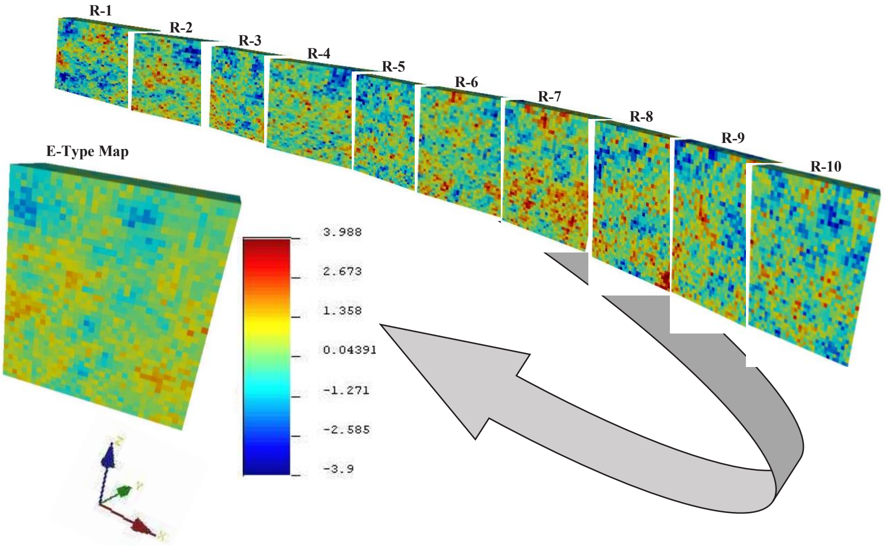


Figure 7. Cu distribution based on simulated data

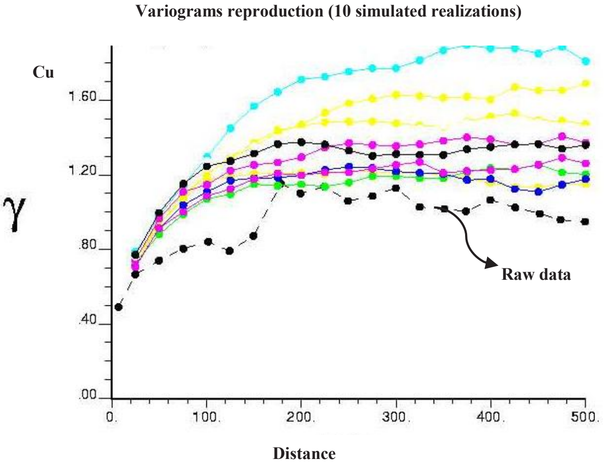


Figure 8. Experimental variograms drawn for raw and simulated data of Cu

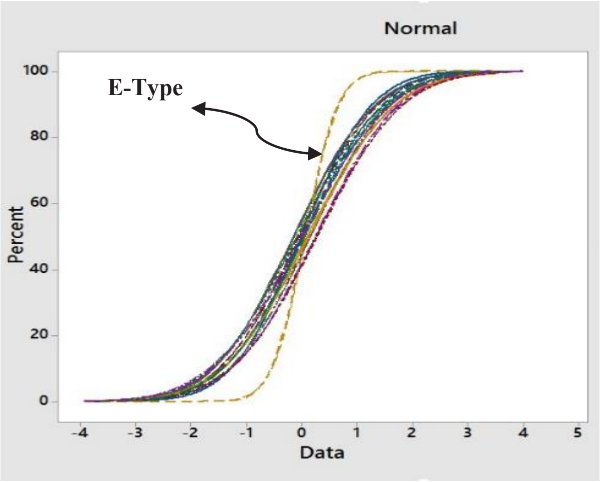


Figure 9. CDFs of 10 realizations, E-type and unsimulated data of Cu

Table 1. Descriptive statistics of raw and simulated boreholes data of the Haftcheshmeh copper deposit (R=Realization)

Raw data	Cu (%)	Simulated data	R-1	R-2	R-3	R-4	R-5	R-6	R-7	R-8	R-9	R-10
No. of samples	2102	No. of samples	16380	16380	16380	16380	16380	16380	16380	16380	16380	16380
Range	2.33	Range	2.9	2.9	2.9	2.9	2.9	2.89	2.9	2.9	2.9	2.9
Min	0	Min	0	0	0	0	0	0	0	0	0	0
Max	2.33	Max	2.9	2.9	2.9	2.9	2.9	2.89	2.9	2.9	2.9	2.9
Mean	0.25	Mean	0.26	0.27	0.32	0.29	0.3	0.27	0.33	0.28	0.28	0.25
Var(%)2	0.026	Var(%)2	0.04	0.07	0.08	0.05	0.09	0.04	0.08	0.05	0.06	0.04
skewness	2.71	skewness	3.91	4.5	3.9	3.7	4.3	3.69	3.7	3.93	3.9	4.2

Table 2. Variogram parameters of Cu raw data and 10 simulated realizations

	Cu-Raw	R-1	R -2	R -3	R-4	R-5	R-6	R-7	R-8	R-9	R-10
Range	227	116	295	206	182	270	133	224	179	141	184
Nugget	0.53	0.54	0.7	0.59	0.64	0.65	0.54	0.7	0.64	0.6	0.63
Partial Sill	0.52	0.65	0.9	0.89	0.55	1.18	0.64	0.65	0.81	0.74	0.6

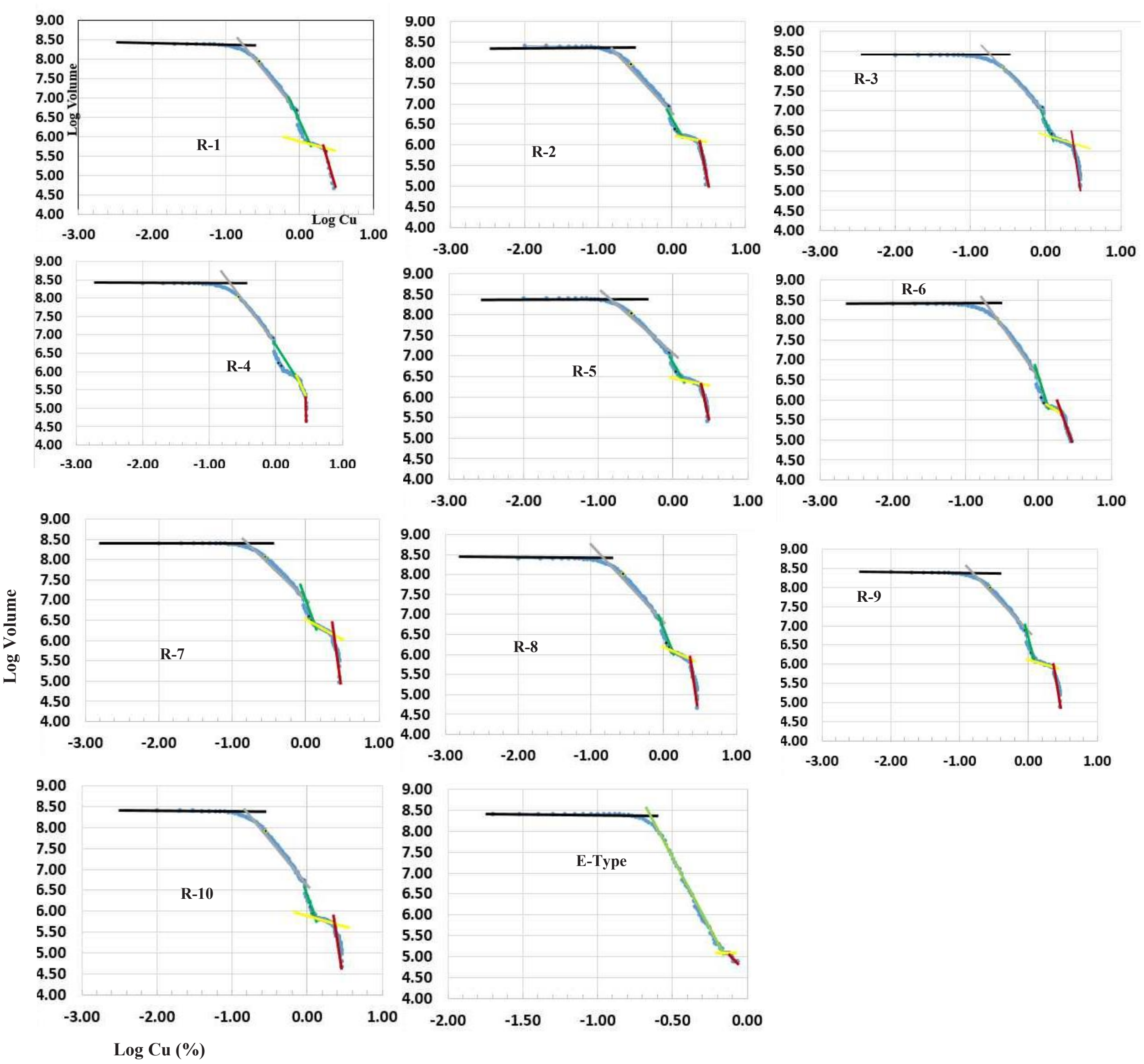


Figure 10. Log-Log plots of simulated realizations

correspond to transitional zones between these two significant alterations. Mineralization with higher Cu concentrations is related to potassic zone in deeper levels. As a result, the western part can be considered as sub economic and any further exploration drilling should be limited to eastern parts for locating Cu mineralization with higher concentrations.

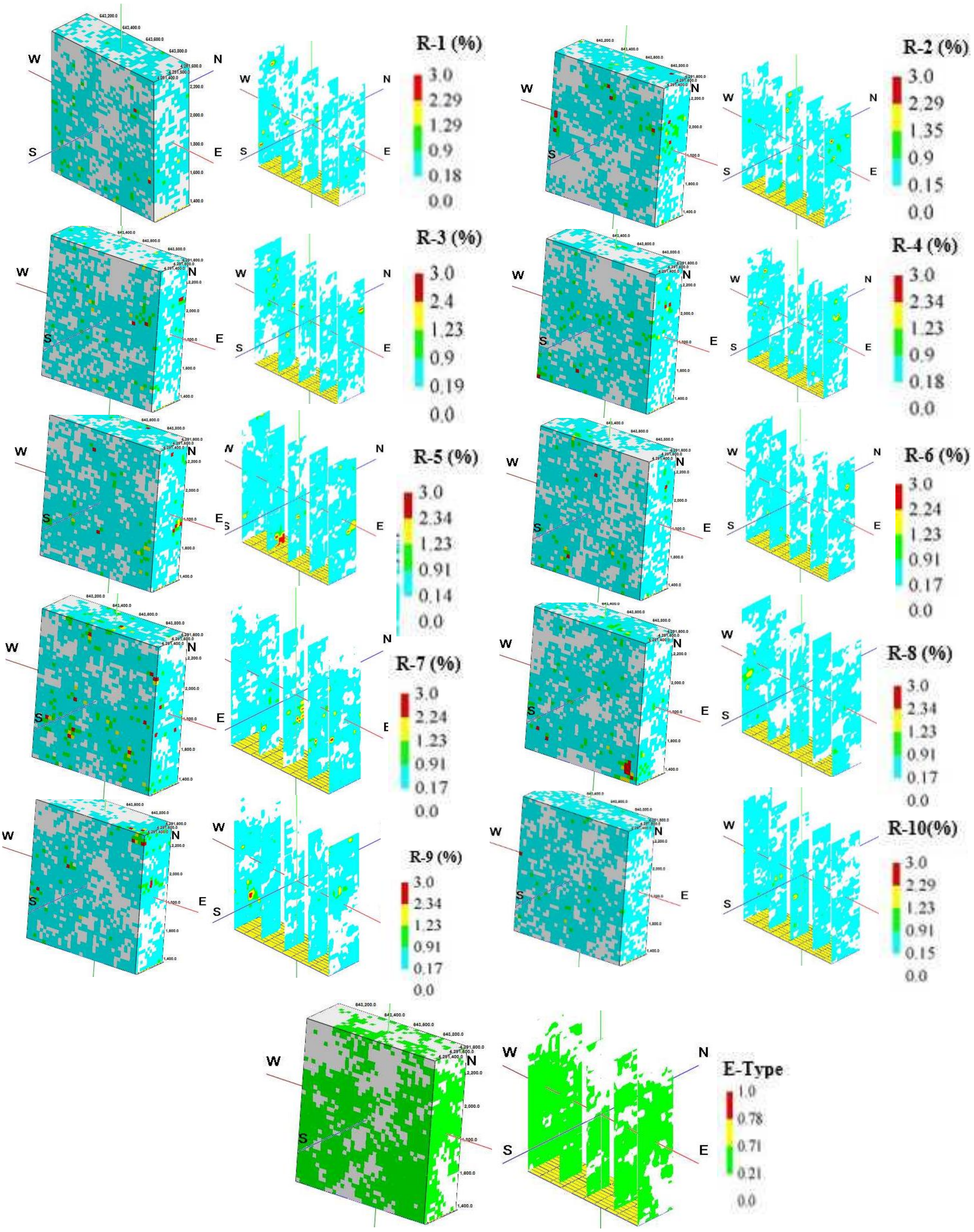


Figure 11. Cu parameters based on C-V fractal model

Table 3. Cu different parameters obtained from C-V Log-Log plots

Realizations	Background (%)	Threshold (%)	Zone-1 (%)	Zone-2 (%)	Zone-3 (%)
R-1	0-0.18	0.18-0.9	0.9-1.29	1.29-2.29	2.29-3
R-2	0-0.15	0.15-0.9	0.9-1.35	1.35-2.29	2.29-3
R-3	0-0.19	0.19-0.9	0.9-1.23	1.23-2.4	2.4-3
R-4	0-0.18	0.18-0.9	0.9-1.23	1.23-2.34	2.34-3
R-5	0-0.14	0.14-0.91	0.91-1.23	1.23-2.34	2.34-3
R-6	0-0.17	0.17-0.91	0.91-1.23	1.23-2.24	2.24-3
R-7	0-0.17	0.17-0.91	0.91-1.23	1.23-2.24	2.24-3
R-8	0-0.17	0.17-0.91	0.91-1.23	1.23-2.34	2.34-3
R-9	0-0.17	0.17-0.91	0.91-1.23	1.23-2.34	2.34-3
R-10	0-0.15	0.15-0.91	0.91-1.23	1.23-2.29	2.29-3

5- CONCLUSIONS

The effective identification, discrimination and detection of Cu mineralization based on authentic method are crucial in a detailed large-scale exploration program. Nevertheless, more precise methods are required for analyzing boreholes datasets. In this study, a stepwise systematic approach was adopted where the boreholes data were imported to the SGSIM (C-V) hybrid method in order to overcome the deficiencies and hindrances of single methods. The comparison between the reality of the field and inferred results show that:

1- SGSIM outputs represented reliable distributions of Cu without smoothing effects.

2- Sequential Gaussian conditional simulation was competent in modeling the spatial uncertainty by generating several realizations. Consequently, uncertainty associated with Cu parameters was reduced. Thereby, the resulting maps demonstrate a well-established spatial geochemical pattern compared to the other geostatistical methods.

3- Here, the C-V fractal model was applied to simulated data. Thereby, the method separated different Cu populations along seven boreholes of the Haftcheshmeh deposit without any preprocessing.

The hybrid SGSIM (C-V) method, shows its capability in delineating promising areas and resulting maps well matching with the major alterations of the area (i.e., potassic zone as well as 2D distribution maps of Cu).

The resulting maps based on the inverse distance weighted method indicate uncertainty between phyllic and potassic zones, as well as conversion of phyllic to potassic at deeper levels with higher concentration of the Cu associated with the potassic zone. Therefore, it is suggested to direct further drilling toward the eastern part of the area in order to locate higher Cu concentration.

4- Based on the highest concentrations of Cu detected by the fused method (Figure 12), the boreholes 9, 16, 23, 31 are more significant than others. In these boreholes the potassic zone is the dominant alteration at depth where granodiorite and quartz diorite are host mineralized zones. Accordingly, complementary explorations should be restricted to mentioned boreholes. Therefore, the precise discrimination of ore bearing alteration zones based on proposed method is a successful approach for ore assessment at depth.

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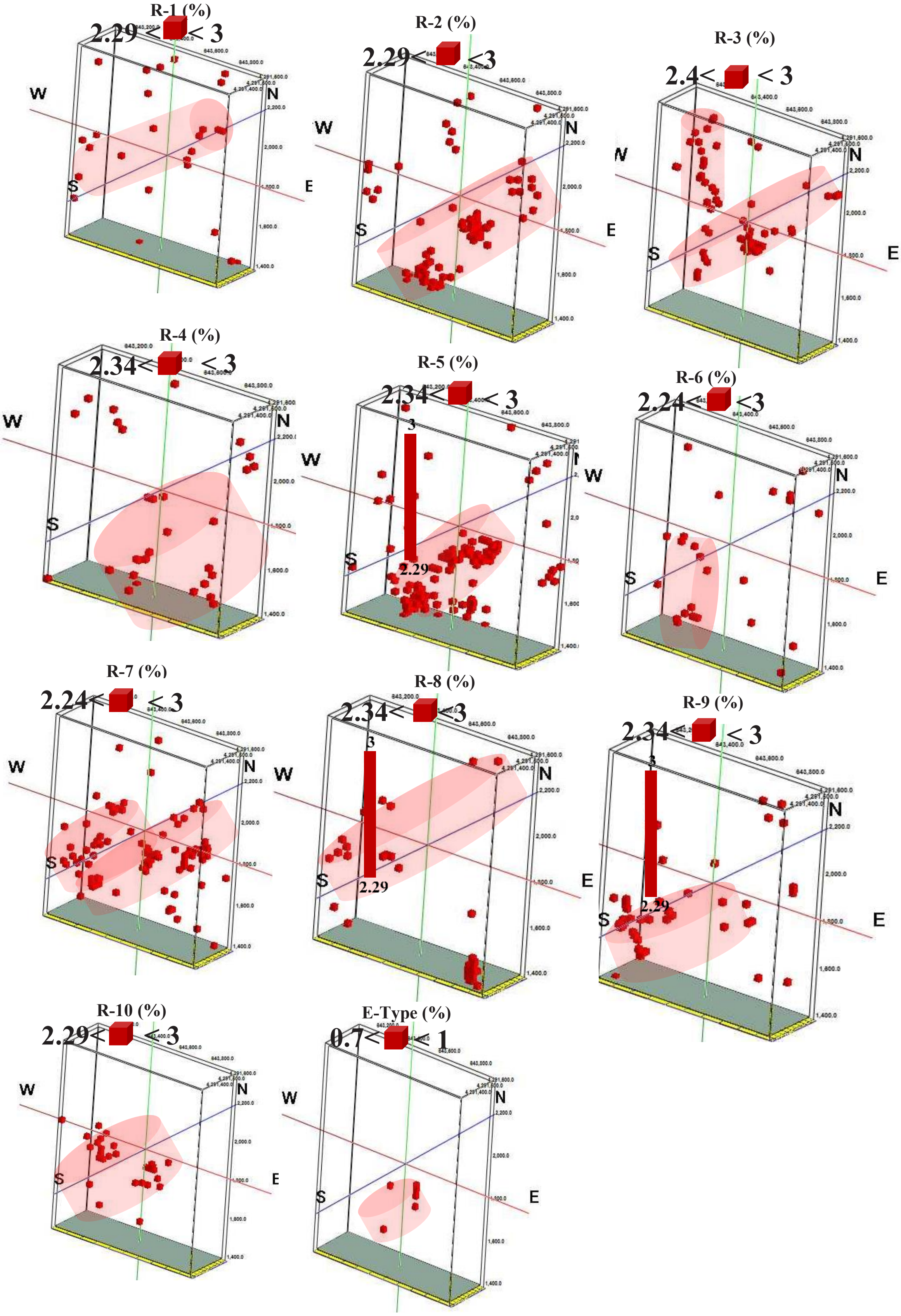

Figure 12. Cu highest concentration maps detected based on C-V fractal

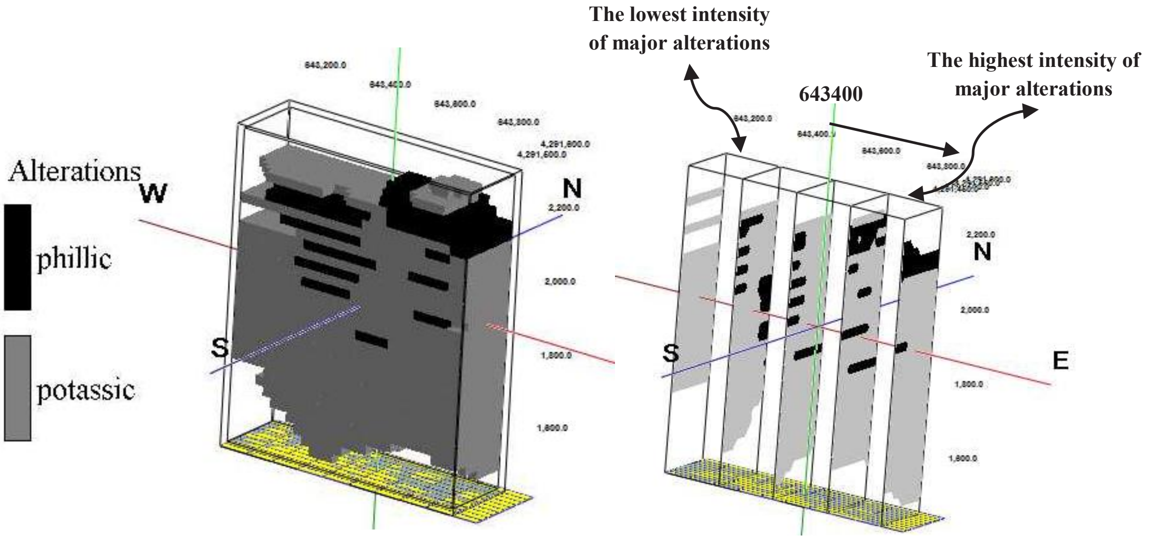

Figure 13. Alteration's map detected based on inverse distance weighted interpolation

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