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Application of multifractal modeling for separation of sulfidic mineralized zones based on induced polarization and resistivity data in the Ghare-Tappeh Cu deposit, NW Iran

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Abstract

The aim of this study was to identify various sulfidic mineralized zones in the Ghare-Tappeh Cu deposit (NW Iran) based on geo-electrical data including induced polarization (IP) and resistivity (RS) using the concentration-volume (C-V) and number-size (N-S) fractal models. The fractal models were used to separate high and moderate sulfidic zones from low sulfidic zones and barren wall rocks. Both the N-S and C-V fractal models confirm that there is a high sulfidic mineralized zone in the NW part of the studied area. Moreover, the application of multifractal modeling based on the geo-electrical data is considered to be a proper approach for delineation of various mineralized zones at depth for optimization of mineral exploration operations. Finally, the results can be useful for proposing grid drilling in a detailed exploration stage.

Keywords: Multifractal modeling, concentration-volume (C-V) fractal model, number-size (N-S) fractal model, Sulfidic mineralized zones, IP/RS, Ghareh-Tappeh

1. Introduction

Recognition of mineralized zones and wall rocks is one of the most important goals in exploration of different types of ore deposits. The induced polarization (IP) and resistivity (RS) methods are applicable tools in mineral exploration, especially in sulfidic base metal deposits (Fink et al. 1990; Flores and Peralta-Ortega 2009; Daneshvar Saein et al. 2012). The IP phenomena are of electrochemical origin and caused either by metallic mineral particles in a rather poorly conducting rock matrix or by differences in the ion concentrations in the pore space or at the interface between the matrix and pore space (Weller et al. 2000; Sumner 2012). Disseminated sulfidic ore minerals produce high values of polarization effects, and IP anomalies are evidence that sulfidic mineralization zones existence in various depths of the deposit (Seigel et al. 1997; Moon et al. 2006). The spectral induced polarization (SIP) method has been used so far for exploration of disseminated ores and mineral discrimination (Hördt et al. 2006). Areas with high values of chargeability and low values of resistivity can be depicted as the association of sulfide ore minerals at depth, specifically in hydrothermal ore deposits (Roth 1977; Khesin et al. 1993; Milsom 2007; Daneshvar Saein et al. 2012). These areas are suitable to explore borehole drilling in the ore deposits because mineralized zones of the deposits, like porphyry deposits, continue to depths of

more than 1000 m (Berger et al. 2008). Mineralized zones in the sulfidic deposits always have lower resistivity and higher chargeability than barren wall rocks because these deposits have high values of sulfidic minerals such as pyrite, chalcopyrite, molybdenite, chalcocite, galena, sphalerite, covelite, and bornite (Cox and Singer 1986; Milsom 2007; Berger et al. 2008).

Fractal geometry, established and developed by Mandelbrot (1983), has a comprehensive usage in various branches of earth sciences (Mandelbrot 1983). According to Turcotte (1989), many phenomena in geosciences such as geophysical properties, comply to fractal models, which adhere to fractal distribution in the case of number of objects N with a characteristic size is greater than r scales in which $N \sim r^{-D} t$ (D : fractal dimension) (Turcotte 1989). The frequency-size distributions for islands, earthquakes, fragments, ore deposits, and oil fields often confirm this relationship.

Application of fractal/multifractal models help better understand geophysical phenomena from the micro to macro levels (Scholz and Mandelbrot 1989; Korvin 1992; Barton et al. 1995; Turcotte 1997; Sagar et al. 2004; Turcotte 2004; Wei et al. 2009). Fractal models are intended for different branches of geophysical exploration, such as separation of geophysical anomalies from the background, geomagnetic polarity and signal analysis, spatial distribution of earthquakes and geo-electrical data interpretation (Turcotte 1997; Malamud and Turcotte 1999; Dimri 2000; Dimri 2005;

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Wei et al. 2009; Daneshvar Saein et al. 2012). Fractal/multifractal modeling also helps to represent relationships of geological, geophysical, and geochemical settings with spatial information derived from the analysis of the mineral deposit occurrence data (Goncalves et al. 2001; Carranza 2009; Afzal et al. 2010; Afzal et al. 2011; Afzal et al. 2012; Hassanpour and Afzal 2013; Meigoony et al. 2014).

Fractal dimensions in geological, geophysical, and geochemical processes correspond to variations in physical features such as lithology, mineralogy, vein and veinlets density or orientation, fluid phases, alteration zones, structural features and so on (Sim et al. 1999; Hassanpour and Afzal 2013). Therefore, fractal dimensions of variations in geophysical data can provide useful information and suitable criteria to discriminate and classify mineralized zones within a studied ore deposit.

Different log-log plots between a geometrical character similar to area, perimeter, or volume and a geophysical attribute parameter such as geo-electrical data in fractal models are appropriate for identifying mineralized zones and geological variations of ore deposits, and classifying geophysical data because threshold values can be delineated as breakpoints in those plots.

The aim of this study was to use concentration-volume (C-V) and number-size (N-S) fractal models to distinguish high sulfidic mineralized zones from others based on the distribution of chargeability and resistivity obtained from IP and RS surveying in the Ghare-Tappeh Cu deposit, which is located in NW Iran.

2. C-V and N-S Fractal Models

The (N-S) model proposed by Mandelbrot (1983) has been expressed as follows (Mandelbrot 1983):

$$N_r(\geq c) = F_c^{-D} \quad (1)$$

where c denotes concentration values of elemental concentrations or geophysical parameters (chargeability and resistivity in the study), $N_r(\geq c)$ the cumulative number of samples with concentration values greater than or equal to c . The concentration of each sample in this formula is related to the fractal dimension (D). Based on this model, Hassanpour and Hassanpour and Afzal (2013) proposed the concentration-number (C-N) for geochemical data interpretation. The N-S fractal model was used to measure the frequency distribution of geophysical parameters based on its number of samples (Deng et al. 2010; Sadeghi et al. 2012; Rahmati et al. 2015).

Afzal et al. (2011) proposed the fractal concentration-volume (C-V) model for recognition of various mineralized zones from barren wall rocks to identify the distribution of major element concentrations associated with the Cu porphyry deposits. This model has the general form of (Afzal et al. 2011):

$$V(\rho \leq v) \propto \rho^{-a1}; V(\rho \geq v) \propto \rho^{-a2} \quad (2)$$

where, $V(\rho \leq v)$ and $V(\rho \geq v)$ denote volumes (V) with elemental concentration or a geophysical parameter values expressed in (ρ). v stands for smaller and values greater than the threshold and $a1$ and $a2$ are characteristic exponents. Simple form of Eq. 1 is expressed as follows:

$$V(\rho) \propto \rho^{-a} \quad (3)$$

In this study, $V(\rho)$ denotes volume with IP or RS values lower than the contour value ρ defining that volume (or zone). There is an inversely relationship between IP and RS values with corresponding volumes.

Based on this definition and description, it is believed that different sulfidic mineralized zones in porphyry Cu-Mo deposits have fractal properties and they can occur where as described by power-law relationships between their chargeability and resistivity and volumetric extensions (Afzal et al. 2011; Daneshvar Saein et al. 2012). In log-log plots of (chargeability or resistivity) contour values versus volumes, certain concentration contours representing breakpoints in the plots are considered threshold values separating geophysical populations in the data. To estimate $V(\rho \leq v)$ and $V(\rho \geq v)$ enclosed by a concentration contour in a 3D block model, in this study, the original data of IP and RS were interpolated by using the inverse distance weighted (IDW) methods. The interpolated 3D block models were used for the purpose of this study. Volumes $V(\rho \leq v)$ and $V(\rho \geq v)$ are equal to the unit volume of a voxel (or volume cell) multiplied by the number of voxels with chargeability or resistivity values (ρ) which are smaller and greater than a certain concentration value (v).

Breakpoints between straight-line segments in the log-log plots correspond to threshold values separating populations of geophysical concentration values instead of mineralization zones due to the distinct geological processes. In porphyry deposits, zones of high chargeability and low resistivity comprise relatively few voxels in a 3D block model. Moreover, the threshold values resulted by the proposed fractal C-V model can show boundaries between different sulfidic mineralized zones and recommended targets for drilling exploration boreholes in sulfidic deposits.

3. Geological setting of study area

Ghare-Tappeh Cu deposit is situated about 14 km NE of Maku, NW Iran (Fig 1). This area is located on the intersection of the Alborz-Azerbaijan structural earth zone and Urumieh-Dokhtar Cenozoic magmatic belt as the main host rocks of Iranian Cu deposits. The main rock types of this deposit consist of limestone, dolomite, and diabasic dykes. Ore minerals include chalcocite, malachite, azorite, bornite, cuprite, and tenorite (Fig 1). There are several faults and fractures that have an effective role on mineralization in the area. Silicification exists in the deposit.

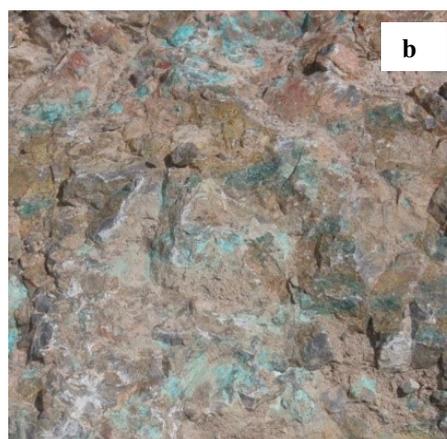
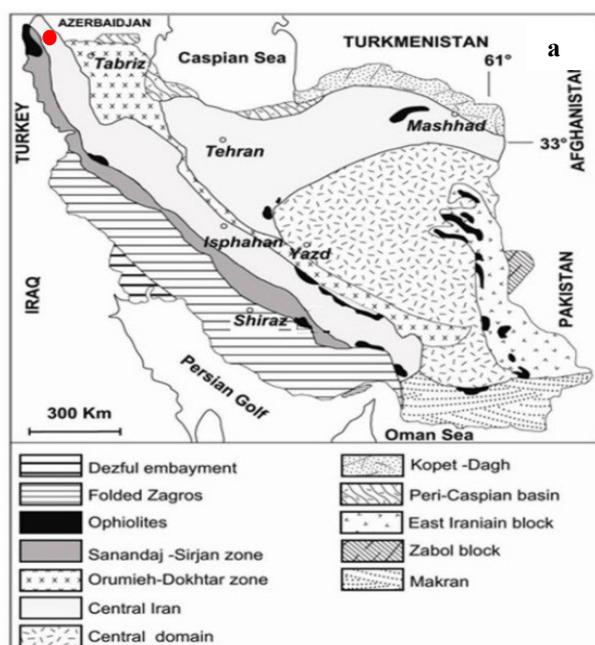


Fig 1. Location of the Ghare-Tappeh Cu deposit in Urumieh-Dokhtar magmatic belt (a) and mineralization observation in the studied area (b)

4. Application of C-V and N-S multifractal modeling

Geo-electrical data was collected along 15 profiles with an approximate length of 7890 m by the Ghare-Tappeh Copper Co. in the deposit as shown in Fig 2.

The IP/RS filed survey used a time domain method with pole-dipole configuration. This survey was performed using an ABEM tetramer SAS1000 (Swiss production). Unit electrode spacing is 10 m and approximate depth penetration is 110 m (Mansourian and Shabankareh 2012). Inverse modeling of chargeability and apparent resistivity resulting from pole-dipole measurements are achieved by UBC-DCIP2D software. The object of inversion consists of finding a conductivity model that can approximate the measured data within the limits of data errors and is in agreement with all prior information. The inversion can be done manually by forward modeling in which changes in the model parameters are made by trial and error until a sufficient agreement between measured and synthetic data is achieved. For more complicated structures, where the number of parameters increases, automatic inversion procedures are recommended (Daneshvar Saein et al. 2012). There are different algorithms for inverse modeling such as smooth models, constrained parametric models and optimum inverse modeling that have been applied for interpreting geophysical data. The optimum inverse model covers both the parametric and smooth model's features and depicts most of the deposit's facts. In this project, both smooth and optimum models, which are the most effective methods in inverse modeling, have been used for geo-electrical data including IP/RS together (Mansourian and Shabankareh 2012).

The correlation between measured chargeability and calculated ones showed low noise in IP data.

Chargeability and resistivity were measured in 4736 points from different depths in these profiles. Chargeability and resistivity were evaluated by estimated block models that were constructed by Rockworks software package using the OK method.

The Ghare-Tappeh deposit is modeled with 692640 voxels and each voxel has a dimension of $10 \text{ m} \times 10 \text{ m} \times 10 \text{ m}$, respectively, whereby the voxel sizes were calculated based on geometrical properties of the deposit and geophysical survey grid dimensions (David 2012). Different volumes occupied with different chargeability and resistivity were calculated for different values of these geophysical parameters in the block model. Threshold values of chargeability (M) and resistivity (p) were recognized from log-log plots (Fig 3).

Depicted values in the log-log plots show their threshold values (breakpoints) separating different straight line segments in the log-log plots. There is an abrupt change in the rate of decreasing the volume enclosed by high values of M and p (Fig 3).

Based on the log-log plots in the C-V fractal model, chargeability (M) has five populations in this deposit. M values higher than 80 mV/V demonstrate high sulfidic zones whereby the slope of the fitted straight line is considered to represent high values of sulfide minerals in the deposit.

Moderate sulfidic zones are determined to range between 39 and 80 mV/V, and the threshold from the left of the IP graph is about 39 mV/V. This is interpreted to be the threshold of the background for the sulfidic mineralization of this deposit (low sulfidic zones and wall rocks) chargeability threshold values defining different sulfidic zones are given in Table 1. Furthermore, the resistivity graph has a clear multifractal nature as depicted in Fig 3(b).

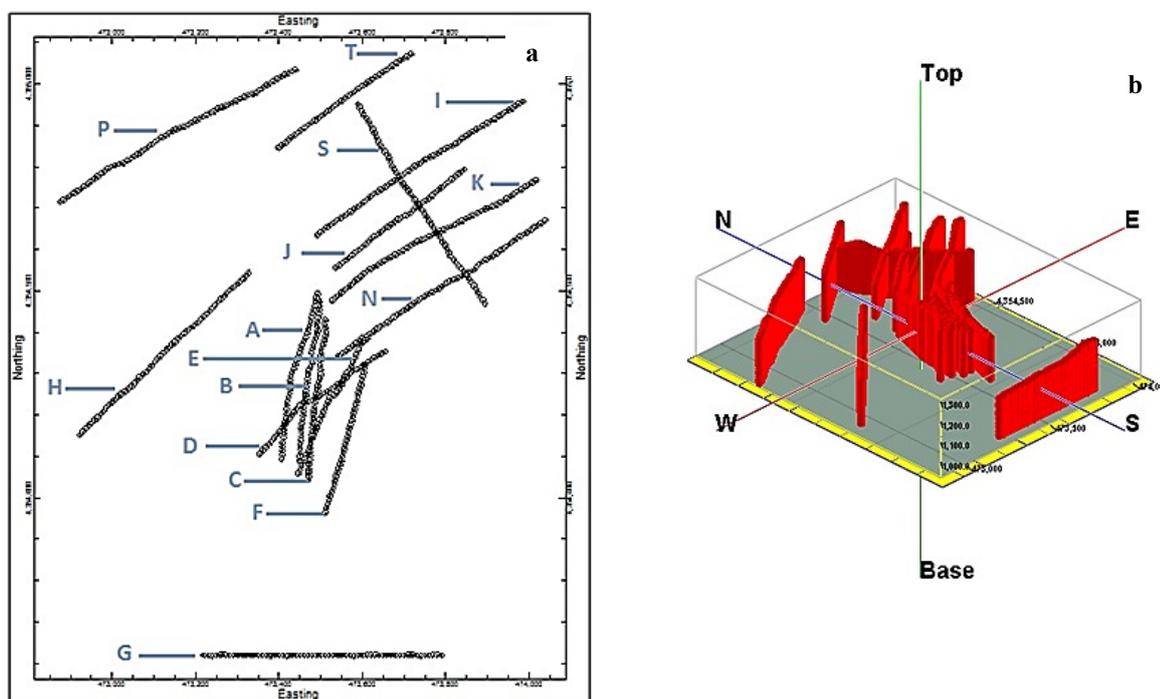


Fig 2. Location of geo-electrical profiles in the studied area (a) and spatial distribution of collected geo-electrical data in the Ghare-Tappeh deposit (surveyed points) (b)

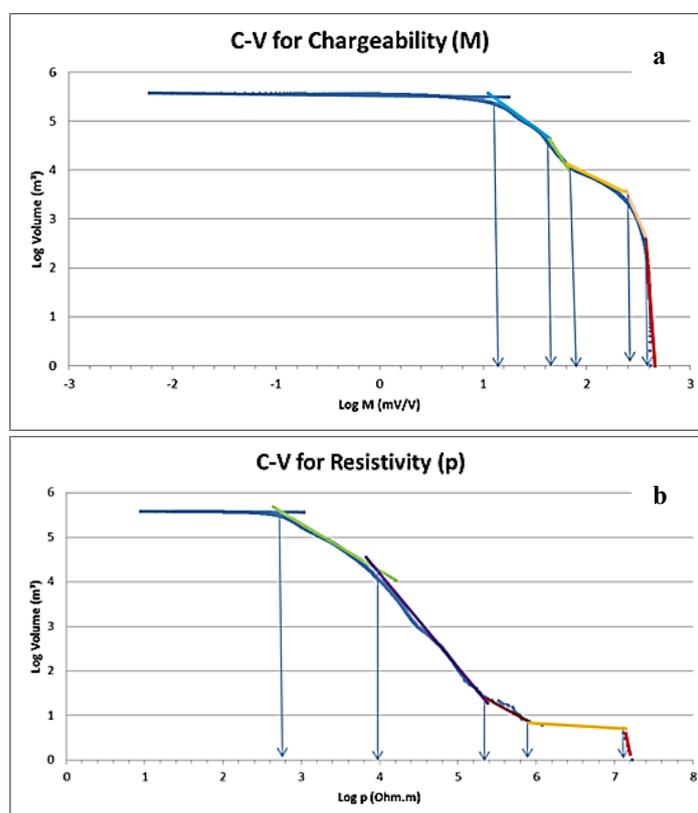


Fig 3. Log-log plots of volume versus chargeability (a) and resistivity (b) based on the C-V fractal model.

There are four populations for resistivity with three threshold values (Table 2) based on the C-V fractal model. The main sulfidic zone is lower than the second threshold value equal to 630 Ohm.m. The low sulfidic mineralization zones are considered to range between the second and third threshold - equal to 10,000 and 199,526 Ohm.m. The high values of resistivity are considered higher than 199,526 Ohm.m, which represent wall rocks.

Based on the N-S model, there are five populations in the chargeability (M) values. Threshold values of chargeability (M) and resistivity (ρ) were identified from the log-log plots (Fig 4). M values higher than

100 mV/V show high sulfidic zones. Moderate sulfidic zones are determined to range between 12 and 100 mV/V, and 12 mV/V is interpreted to be the threshold of the background for the sulfidic mineralization of this deposit (Table 3).

There are four populations in the resistivity as shown in Fig 4. The main sulfidic zone is lower than 630 Ohm.m. The low sulfidic mineralization zones are considered to range between 19,952 and 39,810 Ohm.m (Table 4). High values of resistivity show the wall rocks are higher than 39,810 Ohm.m.

Table 1. Threshold values obtained from the C-V fractal model based on chargeability (mV/V) in the Ghare-Tappeh deposit

Zone	Threshold (mV/V)	Range (mV/V)
Wall rocks	0	0-15
Low sulfidic zones	15	15-39
Moderate sulfidic zones	39	39-80
High sulfidic zones	80	80-251
Extremely high sulfidic zones	251	> 251

Table 2. Threshold values obtained from the C-V fractal model based on resistivity (Ohm.m) in the Ghare-Tappeh deposit

Zone	Threshold (Ohm.m)	Range (Ohm.m)
Wall rocks	199526	> 199526
Low sulfidic zones	10000	10000-199526
Moderate sulfidic zones	630	630-10000
High sulfidic zones	0	< 630

Table 3: Threshold values obtained from the N-S fractal model based on chargeability (mV/V) in Ghare-Tappeh deposit

Zone	Threshold (mV/V)	Range (mV/V)
Wall rocks	0	0-2
Low sulfidic zones	2	2-12
Moderate sulfidic zones	12	12-100
High sulfidic zones	100	100-316
Extremely high sulfidic zones	316	> 316

Table 4: Threshold values obtained from the N-S fractal model based on resistivity (Ohm.m) in the Ghare-Tappeh deposit

Zone	Threshold (Ohm.m)	Range (Ohm.m)
Wall rocks	39810	> 39810
Low sulfidic zones	19952	19952-39810
Moderate sulfidic zones	630	630-19952
High sulfidic zones	0	< 630

According to geo-electrical particulars of the high sulfidic mineralization zone, it can be assumed that the main sulfidic zone has a chargeability higher than 80 mV/V and resistivity lower than 630 Ohm.m as illustrated in Fig 5.

The 3D models of the chargeability and resistivity distributions were made by RockWorks v.15. The various sulfidic zones were separated by a mathematical filter facility of RockWorks software named "Boolean data type". This is a binary knowledge-based model that is used to filter the target (1 or true) from other parts (0 or false). As a result, the studied mineralized zones in the 3D model is allocated binary codes (0 or 1) and the zones with the code number of 0 are removed and zones with the code number of 1 will remain in the 3D model. Another

mathematical facility of the software called multiple of model and model are a tool to manipulate the voxels in a solid model by the corresponding voxels in another equally-dimensioned solid model file that has been intended for combination between chargeability and resistivity models obtained by C-V and N-S fractal models. The high sulfidic zones have been identified to have high values of chargeability (> 80 mV/V) and low values of resistivity (< 630 Ohm.m). Based on the results obtained from the fractal models, main sulfidic mineralized zones were situated in the NW part of the deposit and new targets for drilling borehole exploration can be defined in the area.

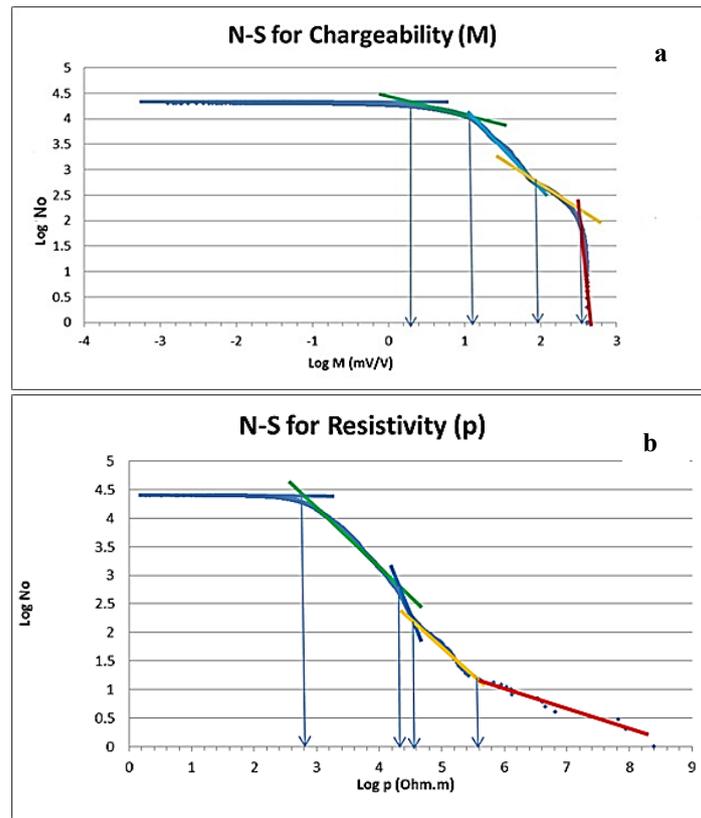


Fig 4. Log-log plots of number versus chargeability (a) and resistivity (b) based on the N-S model.

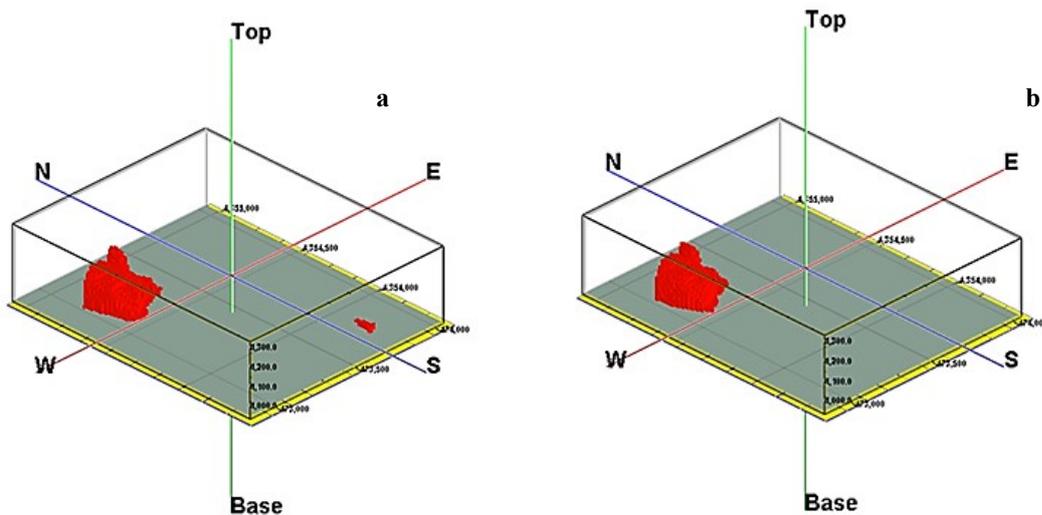


Fig 5. (a) High sulfidic zones with chargeability > 80 mV/V and resistivity lower than 630 Ohm.m using the C-V fractal model, (b) Chargeability > 100 mV/V and resistivity lower than 630 Ohm.m using the N-S fractal model.

5. Conclusions

Results from this study show that the application of fractal models in IP and RS modeling separates different sulfidic mineralized zones in Cu deposits. Determination of targets for exploration drilling can be better understood based on fractal modeling by geo-electrical data. The fractal models could be used for defining sulfidic mineralized zones, especially high accumulation of sulfide minerals from the wall rocks based on obtained IP/RS data. The C-V and N-S fractal models have been successfully applied in order to identify various populations in terms of chargeability and resistivity values in the Ghare-Tappeh Cu deposit. Both C-V and N-S have confirmed that there is a high sulfidic mineralized zone in the NW of the study area. Both of the fractal models correlated with them, especially in resistivity data interpretation. Based on the geological study, clay minerals were situated in the SE part of the area which occurred high values of chargeability and low values of resistivity. This shows that the SE part of the area is a noise. Moreover, the NW part of the studied area is beside of the Cu mineralization.

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