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Nonlinear Processes in Geophysics

Application of concentration-volume fractal method in induced polarization and resistivity data interpretation for Cu-Mo porphyry deposits exploration, case study: Nowchun Cu-Mo deposit, SE Iran

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Abstract. The aim of this study is the utilization of the concentration-volume (C-V) fractal method based on geoelectrical data including induced polarization (IP) and resistivity (RS) in targeting areas hosting different sulfidic mineralization zones in Nowchun Cu-Mo porphyry deposit, SE Iran. The C-V fractal model employed in this research in order to separate high and moderate sulfidic zones from low sulfidic zone and barren wall rocks in the deposit is corresponding to chargeability and resistivity. Results obtained from the C-V method indicate that there is a positive correlation between subsurface mineralization and sulfide mineralized zones; additionally, use of the C-V method based on geophysical data is recognized as an accurate approach for delineation of various mineralization zones in the depth for optimization of mineral exploration operation, particularly in porphyry deposits.

1 Introduction

Different types of ore deposits are associated with various mineralization and alteration types which may affect the physical properties of rocks, minerals and results in a characteristic signature of the deposits (Sandrin et al., 2007). The induced polarization and resistivity methods are applicable tools in mineral exploration especially in sulfidic base metal deposits (Fink et al., 1990; Moon et al., 2005; Flores and Peralta-Ortega, 2009). 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 matrix and pore space (Sumner, 1976; Weller et al., 2000). Disseminated sulfide minerals produce high values of polarization effects and IP anomalies are evidence of sulfide mineralization zones existence in different depths of the deposits (Seigel et al., 1997). The spectral induced polarization (SIP) method has been used so far for exploration of disseminated ores and mineral discrimination (Hördt et al., 2006). Areas within high values of chargeability and low values of resistivity can be depicted as accumulation of sulfide minerals in the depth, specifically in porphyry deposits (Roth, 1977; Khesin et al., 1993; Milsom, 2003). These areas are proper for borehole drilling in porphyry deposits because mineralization zones of the deposits continue to depths of more than 1000 m (Berger et al., 2008). Mineralized zones in porphyry Cu-Mo deposits always have lower resistivity and higher IP than barren host rocks because these deposits have high values of sulfidic minerals such as pyrite, chalcopyrite, molybdenite, chalcocite, covelite and bornite (Cox and Singer, 1986; Berger et al., 2008).

Fractal geometry established and developed by Mandelbrot (1983) is widely applicable in different branches of geosciences. Turcotte (1989) proposed that many phenomena in geosciences, specifically in geophysics, satisfy fractal models which stand for fractal distribution in the case that number of objects N with a characteristic size greater than r scales

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in which $N \sim r^{-D}$ t (D is fractal dimension). The frequency-size distributions for islands, earthquakes, fragments, ore deposits and oil fields often confirm this relation. Application of fractal and multifractal methods has given rise to a better understanding of geophysical phenomena from micro to macro levels, e.g. Schloz and Mandelbrot (1992), Korvin (1992), Barton and La Pointe (1995), Turcotte (1997, 2004), Daya Sagar et al. (2004) and Shen et al. (2009). Fractal methods are intended for different branches of geophysical exploration, such as separation of geophysical anomalies from background, spatial distribution of earthquakes, geomagnetic polarity and signal analysis (Turcotte, 1997; Malamud and Turcotte, 1999; Dimri, 2000, Dimri, 2005; Shen et al., 2009). Fractal methods also serve to depict relationships of geophysical, geological and geochemical settings with spatial information derived from analysis of mineral deposit occurrence data (Turcotte, 1997; Goncalves et al., 2001; Dimri, 2005; Carranza, 2009; Afzal et al., 2010; Zia Zarifi et al., 2010; Afzal et al., 2011). Fractal dimensions in geological, geochemical and geophysical processes correspond to variations in physical attributes such as mineralogy, vein and veinlets density or orientation, fluid phases, alteration zones, structural feature and so on (Turcotte, 1997; Sim et al., 1999; Carranza, 2009; Afzal et al., 2011). Therefore, fractal dimensions of variations in geophysical data can provide useful information and applicable criteria to identify and categorize mineralized zones within a studied ore deposit. Various log-log plots between a geometrical character such as area, perimeter or volume and a geophysical quality parameter like geoelectrical data in fractal methods are appropriate for distinguishing geological recognition and populations' classification in geophysical data because threshold values can be identified and delineated as breakpoints in those plots. These geophysical threshold values are usually correlated by geological data in different types of ore deposits.

The aim of this study is to apply a concentration-volume (C-V) fractal method to discriminate high mineralized sulfidic zones from others based on the distribution of chargeability and resistivity achieved by IP and RS in the Nowchun Cu-Mo porphyry deposit located in SE Iran. Furthermore, results defined by chargeability and resistivity threshold values are correlated with boreholes carried out in this deposit to validate the efficiency of the proposed C-V method with Cu and Mo concentrations data. To do this, 3-D analysis of geophysical distribution has been conducted to have a better understanding for interpretations of the C-V model.

2 Fractal concentration-volume method

Afzal et al. (2011) proposed the fractal concentration-volume (C-V) model for delineating different mineralization zones from barren host rocks in order to identify the distribution of major element concentrations associated with the Cu porphyry deposits. This model has the general form of

$$V(\rho \le \upsilon) \infty \rho^{-a1};\, V(\rho \ge \upsilon) \infty \rho^{-a2} \qquad (1)$$

where $V(\rho \le \upsilon)$ and $V(\rho \ge \upsilon)$ denote volumes (V) with elemental concentration or a geophysical parameter values expressed in (ρ); (υ) stands for values smaller and greater than threshold and $a1$, $a2$ are characteristic exponents. Simple form of Eq. (1) as follow:

$$V(\rho) \infty \rho^{-a}. \qquad (2)$$

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 (Afzal et al., 2011) and they can occur, as described by power-law relationships, between their chargeability and resistivity and volumetric extensions. 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 $V(\rho \le \upsilon)$ and $V(\rho \ge \upsilon)$ enclosed by a concentration contour in a 3-D block model, in this study, the original data of IP and RS were interpolated by using the ordinary kriging (OK) method. The interpolated 3-D block models were used for the purpose of this study. Volumes $V(\rho \le \upsilon)$ and $V(\rho \ge \upsilon)$ 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 (υ).

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 3-D block model. Moreover, threshold values resulting in the proposed fractal C-V model can represent boundaries between different sulfidic mineralization zones and recommended targets for drilling exploration boreholes in Cu-Mo porphyry deposits.

3 Geological setting of case study

Nowchun Cu-Mo porphyry deposit is situated about 65 km south of Rafsanjan and 4 km SW of Sarcheshmeh copper mine which is the biggest Iranian copper mine, SE Iran (Fig. 1). This deposit is located in SE part of main Iranian Cenozoic magmatic belt, named Urumieh-Dokhtar, and extends 1700 km and 150 km wide from NW to SE Iran, as shown in Fig. 1 (Alavi, 1994; Shahabpour, 1994; Alavi, 2004; Dargahi et al., 2010; Afzal et al., 2010). This belt has been interpreted to be a subduction related Andean-type

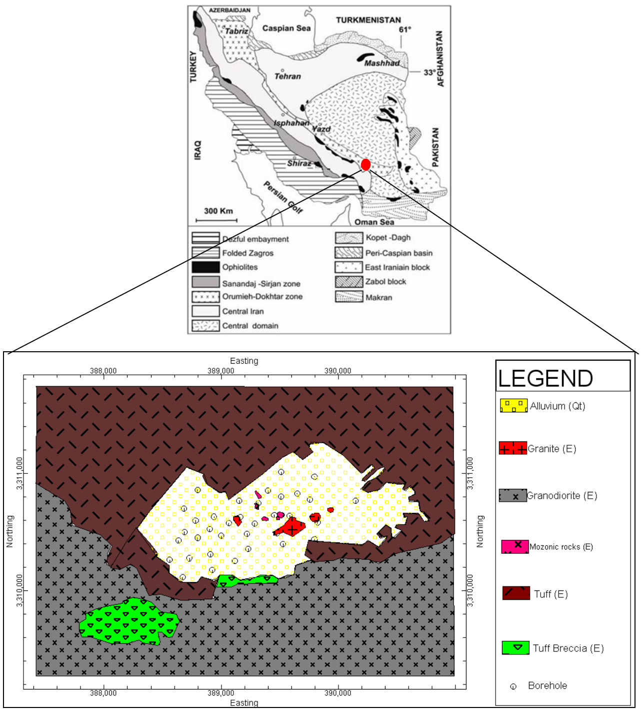

Fig. 1. Location of Nowchun Cu-Mo porphyry deposit in Urumieh-Dokhtar magmatic belt modified based on Alavi (1994) and simplified geological map of Nowchun deposit and its boreholes locations.

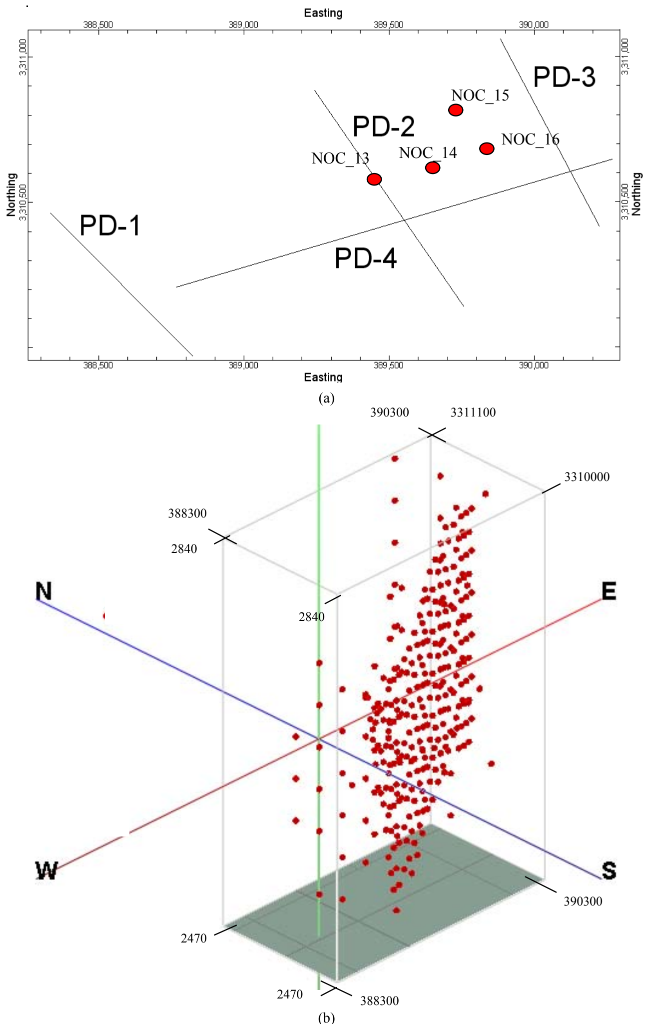

Fig. 2. (a) Location of geoelectrical profiles and location map of mineralized boreholes in the study area and **(b)** spatial distribution of collected geoelectrical data in Nowchun deposit (red dots are surveyed points for geoelectrical parameters consist of chargeability and electrical resistivity with vertical exaggeration of 8.34).

magmatic arc that has been active from the Late Jurassic to the present. The rock types of this belt are composed of voluminous tholeiitic, calc-alkaline, and K-rich alkaline intrusive and extrusive rocks with associated pyroclastic and volcanoclastic successions, along the active margin of the Iranian plates (Berberian and King, 1981; Dargahi et al., 2010). This belt hosts the famous Iranian porphyry deposits, such as Sarcheshmeh, Sungun, Meiduk, Kahang and Darehzar (Shahabpour, 1994; Atapour and Aftabi, 2007; Boomeri et al., 2009; Afzal et al., 2010).

Based on Yugoslavian geologists exploration in 1972, there is an Eocene volcano-sedimentary complex consisting of granite, diorite-granodiorite and tuff rocks, as depicted in Fig. 1 also Eocene andesitic units surround the complex and alterations. Porphyry Dioritic and granodioritic units extend in the southern part of the study area, adjusted to the granite. There are two major structural features with trends of E–W and NE–SW faults (BEOGRAD-Yugoslavia, 1972).

Alteration zones include potassic, phyllic, argillic and propylitic in this deposit. Argillic zone occupies several parts in this area but phyllic has been scattered in the most parts of the deposit. The Cu mineral occurrences are not very numerous and consist mostly of malachite and azurite within quartz veins, and veinlets contain chalcopyrite in several parts of the area. Sulfide minerals consist of pyrite, chalcopyrite, molybdenite, galena, sphalerite, tetrahedrite, pyrrhotite, marcasite, chalcocite, bornite and covelite. Pyrite, chalcopyrite and molybdenite are abundant exists in this area.

4 Application of concentration-volume fractal

Geoelectrical data was collected along 4 profiles with approximate length of 4400 m by Saman Kav consulting engineers Co. (2008) in Nowchun deposit, as shown in Fig. 2. The surface IP/RS field survey used the time domain method with a pole-dipole configuration. The current field survey used a dipole spacing of 40 m. This survey was performed using a GDDTX2 transmitter and IPR-12 receiver manufactured by Scintrex of Canada limited. Unit electrode spacing is 40 m and approximate depth penetration is 250 m, with pole- dipole array (Saman Kav consulting engineers Co., 2008). Inverse modeling of chargeability and apparent resistivity data resulting from pole-dipole measurements are achieved by RES2DINV software. The objective of inversion consists of finding a conductivity model which 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.

The inversion algorithm used is applicable to variable electrode configurations including buried electrodes, which has been applied to several tomographic problems to solve systems of linear equations (Dines and Lytle, 1979; Van der Sluis and Van der Vorst, 1987). It can be used for both 2-D and 3-D inversion. Since the number of grid elements is generally much higher than the number of measured data, a strongly underdetermined system has to be solved.

The RES2DINV program uses the smoothness-constrained least-squares method inversion technique to produce a 2-D model of the subsurface from the chargeability and apparent resistivity data (Rucker et al., 2011). It is completely automatic and the user does not even have to supply a starting model. This program has been optimized for the inversion of large data sets. The blocky inversion algorithm was used for geoelectrical data analysis by RES2DINV software.

The program will automatically choose the optimum inversion parameters for a particular data set. However, the parameters which affect the inversion process can be modified by the user. Three different variations of the least-squares method are provided; a very fast quasi-Newton method, a slower but more accurate Gauss-Newton method, and a moderately fast hybrid technique which incorporates the advantages of the quasi-Newton and Gauss-Newton methods. The smoothing filter can be adjusted to emphasize resistivity variations in the vertical or horizontal directions. Two different variations (Chargeability and resistivity) of the smoothness constrained least-squares method are provided: one optimized for areas where the subsurface resistivity varies in a smooth manner and another optimized for areas with sharp boundaries. A robust data inversion option is also available to reduce the effect of noisy data points. Chargeability and resistivity information from boreholes and other sources can also be included to constrain the inversion process.

Correlation between measured chargeability data and calculated ones shows low noise in IP data. In this model, the probable depth of mineralization commences at about 30–50 m from the surface. Chargeability and resistivity were measured at 302 points from different depths in these profiles. Chargeability and resistivity evaluated by estimated block models which were constructed based on ordinary kriging (OK) method by RockWorks™ v. 15 software

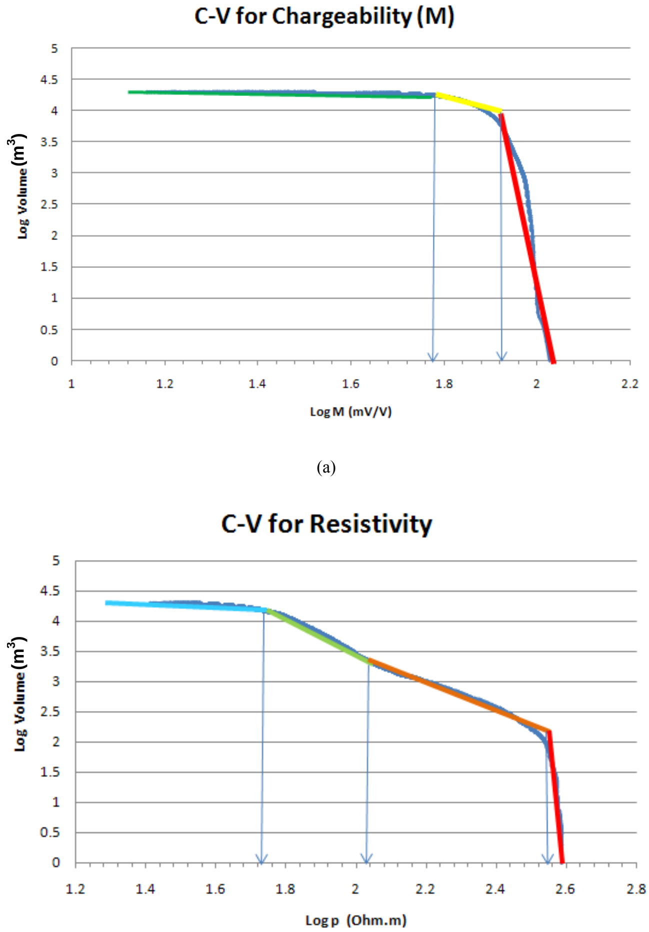

Fig. 3. Log-log plots of volume versus chargeability **(a)** and resistivity **(b)** in the Nowchun deposit.

package. The Nowchun deposit is modeled with 19 864 voxels that have projected dimensions of $2000 \times 1100 \times 740$ m in X, Y and Z, and each voxel has a dimension of $50 \times 50 \times 10$ m, respectively, whereby the voxel sizes were calculated based on geometrical properties of deposit and geophysical survey grid dimensions (David, 1970). Different volumes occupied by different chargeability or resistivity ($V(\rho \leq \upsilon)$ and $V(\rho \geq \upsilon)$ in Eq. 1) were calculated for different values of these geophysical parameters in the block model. Thresholds values of chargeability (M) and resistivity (ρ) were recognized from log-log plots (Fig. 3), which reveal a power-law relationship between the geoelectrical parameters and volumes occupied. Depicted arrows in log-log plots show their threshold values (breakpoints) separating different straight lines segments in the log-log plots. There is a sudden change in the rate of decrease of the volume enclosed by high values of M and ρ (Fig. 3).

Based on the log-log plots, chargeability (M) has three populations in this deposit. M values higher than 83 mV V^{-1} demonstrate high sulfidic zones whereby the slope of the fitted straight line is considered to represent high value of

Table 1. Threshold values obtained by using the C-V method based on Chargeability (mV V^{-1}) in Nowchun deposit.

Zone	Threshold (mV V^{-1})	Range (mV V^{-1})
Wall rocks and low sulfidic zone	–	0–56
Moderate sulfidic zone	56	56–83
High sulfidic zone	83	$>$ 83

Table 2. Threshold values obtained by using the C-V method based on resistivity (Ω m) in Nowchun deposit.

Zone	Threshold (Ω m)	Range (Ω m)
Wall rocks	355	$>$ 355
Low sulfidic zone	105	105–355
Moderate sulfidic zone	52	52–105
High sulfidic zone	–	$<$ 52

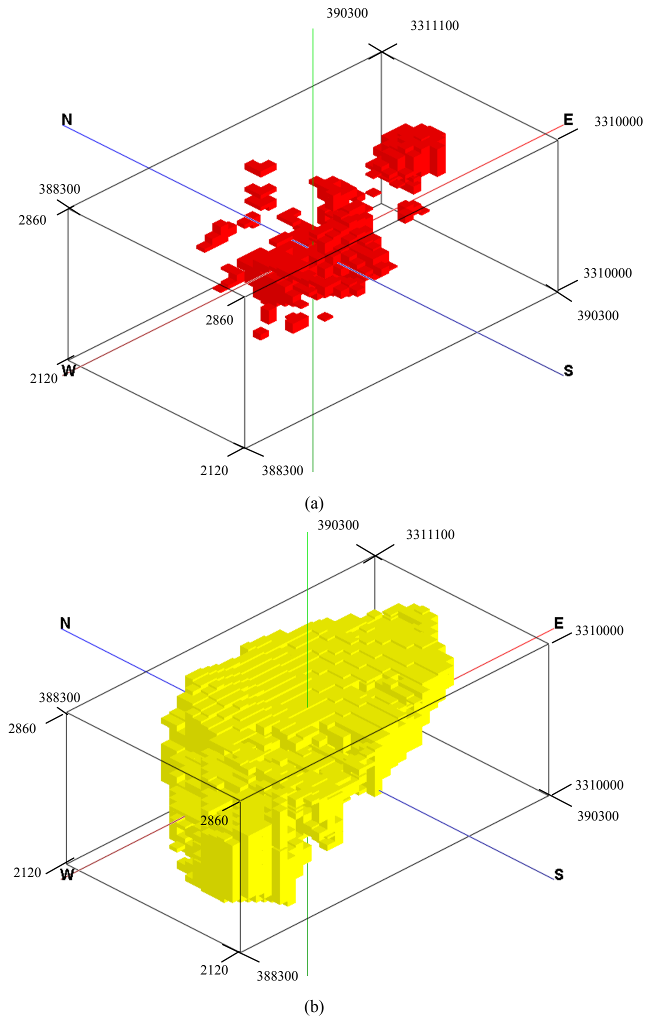

Fig. 4. The high sulfidic with chargeability $>$ 83 mV V^{-1} and resistivity $<$52 Ω m **(a)** and moderate sulfidic chargeability 56–83 mV V^{-1} and resistivity 52–105 Ω m **(b)** zones of Nowchun deposit determined by the C-V method.

sulfide minerals in the porphyry deposit. Moderate sulfide zones are determined to range between 56 and 83 mV V^{-1}, and the first threshold from the left of the IP graph is about 56 mV V^{-1} that is interpreted to be the threshold of background for the sulfidic mineralization of this deposit (low sulfidic zone and wall rocks). Chargeability threshold values defining different sulfidic zones are given in Table 1. Furthermore, resistivity (ρ) graph has a clear multifractal nature which can be interpreted that there are two main stages for Cu-Mo sulfidic mineralization, as depicted in Fig. 3. There are four populations for resistivity with three threshold values, as presented in Table 2. Main sulfidic zone is lower than second threshold value equal to 105 Ω m that the best part of sulfidic mineralization zone correlates with resistivity lower than first threshold of ρ equal to 52 Ω m. Low sulfide mineralization zone is considered to range between second and third threshold equal to 105 and 355 Ω m. High values of resistivity are considered higher than 355 Ω m which represent wall rocks. According to geoelectrical particulars of high sulfidic mineralization zone, it can be considered that the main sulfidic zone has chargeability higher than 83 mV V^{-1} (the last population in the chargeability log-log plot) and lower than 52 Ω m (the first population), as illustrated in Fig. 3. It can be interpreted that moderate sulfidic zone has chargeability values in the range of 56 and 83 mV V^{-1} and resistivity values in the range of 52 and 105 Ω m. Wall rocks and low sulfidic zone can be considered to the range of higher than 105 Ω m and lower than 56 mV V^{-1} for resistivity and chargeability, respectively.

3-D models of chargeability and resistivity distributions were generated by RockWorks™ v. 15. The various sulfidic zones were identified by a mathematical filter facility of RockWorks software which is called “Boolean data type”. As a result of that, the studied mineralized zone in the 3-D model is allocated with binary codes (zero or one) which represent that the zones with the code number of zero are removed and zones with the code number of one will remain in the 3-D model. This tool transforms a real number solid model file to a Boolean (true/false) file. In this process, the chargeability or resistivity values of voxels are set to “1” if their original values fall within a user-specified range and to a “0” if the values do not fall within the range. Other mathematical facility of the software called multiple of model & model as a tool to manipulate the voxels in a solid model by the corresponding voxels in another equally-dimensioned solid model file has been intended for combination between chargeability and resistivity models obtained by the C-V fractal method. The high sulfidic zones achieved by the C-V method illustrate high values of chargeability (more than 83 mV V^{-1}) and low values of resistivity ($<$ 52 Ω m)

Table 3. Statistical parameters of Cu and Mo in NOC_13, NOC_14, NOC_15 and NOC_16 drilled boreholes in Nowchun deposit.

Borehole No.	Maximum Cu (%)	Minimum Cu (%)	Maximum Mo (ppm)	Minimum Mo (ppm)
NOC_13	1.06	0.02	2500	5
NOC_14	1.02	0.05	1218	19
NOC_15	1.19	0.06	3197	26
NOC_16	2.46	0.05	1900	13
Borehole No.	Maximum Cu (%)	Minimum Cu (%)	Maximum Mo (ppm)	Minimum Mo (ppm)
NOC_13	0.14	0.09	151	114
NOC_14	0.25	0.22	218	105
NOC_15	0.24	0.2	286	211
NOC_16	0.22	0.18	255	190

which occur in the central and eastern parts of this deposit, as depicted in Fig. 4. In other words, high sulfidic zones are known as the zones with chargeability > 83 mV V^{-1} and resistivity <52 Ohm.m. Moderate sulfidic zones (chargeability between 56 and 83 mV V^{-1} and resistivity between 52 and 105 Ω m) obtained by the *C-V* method is situated in the depth along with high sulfidic zone extended with the trend of NE–SW in this deposit, as shown in Fig. 4. Based on results from the *C-V* method, the central and eastern parts of this deposit can be proper for detailed exploration.

5 Comparison with exploration drills information

Sulfidic mineralization zones derived via the *C-V* method based on geoelectrical data are compared and correlated with information from drilled exploration boreholes and correspondingly lithogeochemical samples analyzed by the ICP-MS method for measuring Cu, Mo and related elements of the study area. There are several exploration boreholes, i.e. NOC13, NOC14, NOC15, and NOC16 which were drilled in the central and eastern parts of the deposit as presented in Fig. 5. Maximum Cu and Mo grades are 1.06 % and 2500 ppm in NOC13, Cu and Mo grades are 1.02 % and 1218 ppm in NOC14, 1.19 % and 3197 ppm for Cu and Mo in NOC15 and 2.46 % and 1900 ppm for Cu and Mo in NOC16. As a result, these boreholes were drilled in the high sulfidic mineralization zone based on the *C-V* method as shown in Table 3. Cu and Mo means and medians in the boreholes are proper for mineralization, as depicted in Table 3. Cu and Mo means in NOC_14, NOC_15 and NOC_16 are higher than 0.2 % and 200 ppm, respectively. Sulfide minerals of Pb and Zn are an indicator for sulfur enrichment and occurrence of sulfidic zones. Increase of Pb and Zn values with Cu and Mo values in the boreholes illustrates, correspondingly, rise in terms of sulfidic zones and sulfur enrichment in the studied area (Laznicka, 2006).

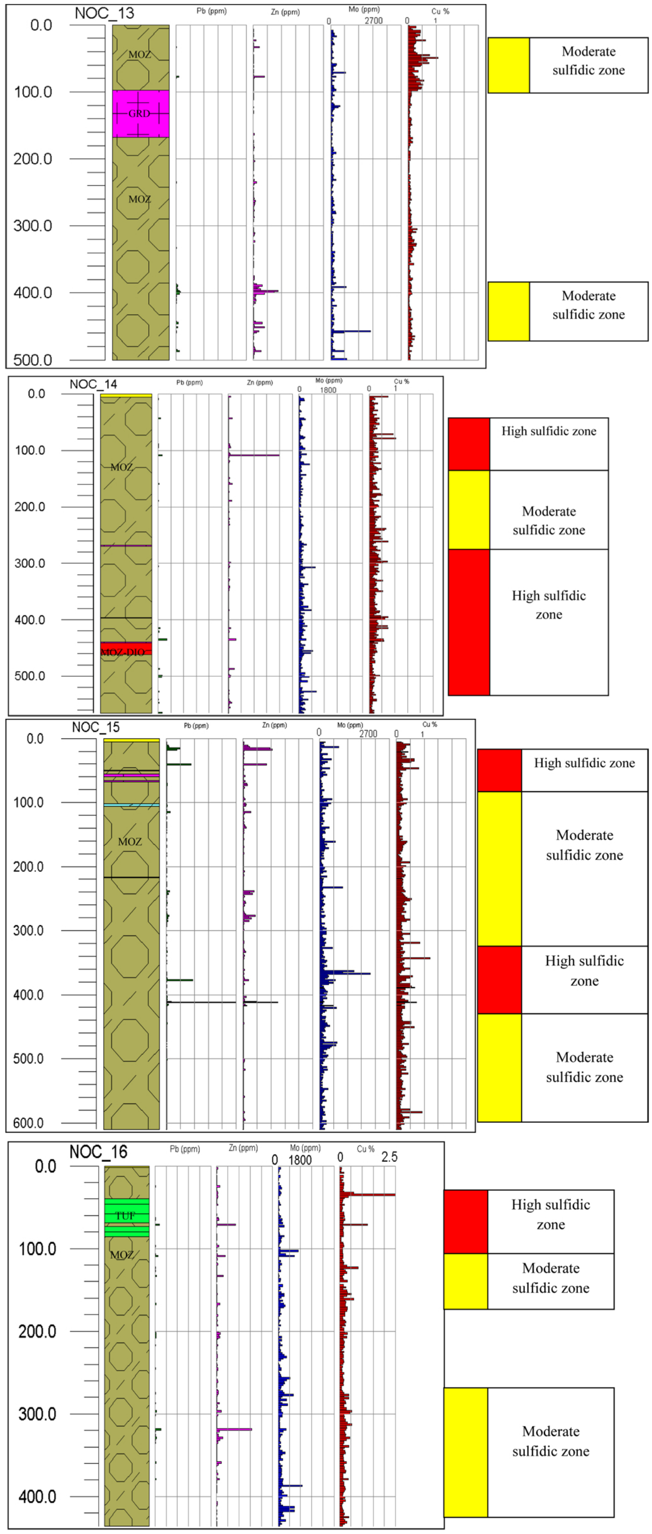

Fig. 5. Log sheets of NOC_13, NOC_14, NOC_15 and NOC_16 in Nowchun deposit and comparison between elemental grades and sulfidic zones derived via the *C-V* model.

Correlation between rock types and sulfidic zones resulted by the C-V model indicates that the sulfidic zones are associated with monzonitic rocks. However, wall rocks based on the C-V model (considering Fig. 1) have a strong correlation with granodiorite and tuff units.

6 Conclusions

Results from this study show that the application of the the C-V method in IP and RS modeling distinguishes different sulfidic mineralization zones in Cu-Mo porphyry deposits. Determination of targets for drilling exploration boreholes can be better understood via the C-V fractal method based on geoelectrical data such as chargeability and resistivity in these deposits. The fractal method could be applied for defining sulfidic mineralized zones, especially high accumulation of sulfide minerals from the wall rocks, or from the background, based on data obtained from IP/RS exploration.

The C-V fractal method has been successfully applied in order to identify different populations in terms of chargeability and resistivity values with their volumes within the Nowchun Cu-Mo porphyry deposit. The C-V log-log plot based on resistivity reveals that there are two major sulfidic mineralization stages. The main sulfidic mineralization zone has a chargeability higher than 83 mV V^{-1} and a resistivity lower than 52 Ω m, which is situated in the central and eastern parts of the deposit. The moderate sulfidic zone is deep and has a NE–SW trend with chargeability values in the range of 56 and 83 mV V^{-1} and resistivity values in the range of 52 and 105 Ω m. The high and moderate sulfidic zones identified via the C-V method are associated with high values of Cu and Mo in regard to both elements' grades according to the collected lithogeochemical samples of the drilled boreholes. Boreholes NOC_13, NOC_14, NOC_15 and NOC_16 were drilled in the sulfidic zones according to the C-V model and analyzed samples show that there are Cu and Mo values higher than 1 % and 1500 ppm, respectively, which can be interpreted that the central and eastern parts of the deposit are proper for detailed exploration and drilling new exploration boreholes.

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