Complex resistivity of mineral rocks in the context of the generalized effective-medium theory of the IP effect

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Summary

One of the major problems in mineral exploration is the inability to reliably distinguish between economic mineral deposits and uneconomic mineralization. While the mining industry uses many geophysical methods to locate mineral deposits, until recently, there was no reliable technology for identification and characterization of mineral resources. The main goal of this paper is an application of the generalized effective-medium theory of induced polarization (GEMTIP) to studying the complex resistivity of typical mineral rocks. We collected representative rock samples from the Cu-Au deposit in Mongolia, and subjected them to the mineralogical analysis using Quantitative Evaluation of Minerals by Scanning Electron Microscopy (QEMSCan) technology. We also conducted an analysis of the electrical properties of the same samples using the laboratory complex resistivity (CR) measurement system. As a result, we have established relationships between the mineral composition of the rocks, determined using QEMSCan analysis, and the parameters of the GEMTIP model defined from the lab measurements of the electrical properties of the rocks. These relationships open the possibility for remote estimation of types of mineralization using spectral IP data.

Introduction

The physical-mathematical principles of the IP effect were originally formulated in the pioneering works of Wait (1959, 1982) and Sheinman (1969). However, the IP method did not find wide application in mineral exploration until the 1970's with the work of Zonge (e.g., Zonge, 1974; Zonge and Wynn, 1975) and Pelton (Pelton et al., 1977, Pelton, 1978). Significant contributions were also made by Kennecott research team between 1965 and 1977 (e.g., Nelson, 1997). Over the last 40 years several conductivity relaxation models have been developed, which provided quantitative characterization of the electric charging phenomena, including the empirical Cole-Cole model (Cole & Cole, 1941; Pelton et al., 1978), electrochemical model of Ostrander & Zonge (1978), the GEMTIP model of Zhdanov (2008), based on generalized effective-medium theory of induced polarization, and electrochemical model of Revil et al. (2013). The GEMTIP resistivity model uses the effective-medium theory to describe the complex resistivity of heterogeneous rocks and incorporates the physical and electrical characteristics of rocks at the porous/grain scale and translates them into an analytic expression for the effective complex resistivity. It was shown in the paper by Zhdanov (2008) that the widely accepted Cole-Cole model is a special case of the GEMTIP model, where all the grains have a spherical shape. In the present paper, we investigate a more general case with the grains having elliptical shape. By choosing different values of the ellipticity coefficient, one can consider the oblate or prolate ellipsoidal inclusions, which provides a wide class of models to be used in the analysis of the complex conductivity of the mineral rocks.

An important goal of this paper is an application of the developed GEMTIP models to studying the complex resistivity of the typical mineral rocks. We have collected several dozens of representative rock samples from the Cu-Au deposit in Mongolia. These rock samples were subjected to the mineralogical analysis using Quantitative Evaluation of Minerals by Scanning Electron Microscopy (QEMSCan) technology. We also conducted an analysis of the electrical properties of the same samples using laboratory complex resistivity (CR) measurement system.

As the result of this study, we have established the relationships between the mineral composition of the rocks, determined using QEMScan analysis, and the parameters of the GEMTIP model defined from the lab measurements of the electrical properties of the rocks. These relationships open a possibility for remote estimation of the type of mineralization using the spectral IP data.

Multiphase heterogeneous medium filled with ellipsoidal inclusions

The GEMTIP model provides a general solution of the effective conductivity problem for an arbitrary multiphase composite polarized medium (Zhdanov, 2008, 2009, 2010). The GEMTIP theory opens a possibility of determining the effective conductivity for grains with arbitrary shape; however, the calculation of the parameters of the GEMTIP model may become very complicated. In a special case of inclusions with spherical shape, the GEMTIP model can be reduced to the classical Cole-Cole model of complex resistivity. There exists another special case of inclusions with ellipsoidal shape, where the solution of the GEMTIP formulas can be obtained in close form, similar to a model with spherical inclusions. The advantage of the model with ellipsoidal inclusions is that in this case one can use different shapes of ellipsoids, from oblate to prolate, to model different types of heterogeneous rock formations and different types of inclusions (see Figure 1). The three-phased GEMTIP model, developed by Zhdanov (2008), in a case of ellipsoidal inclusions representing different minerals, can be described by the following formula:

$$\rho_e = \rho_0\{1 + \sum_{l=1}^{2}\sum_{\alpha=x,y,z}\frac{f_l}{3\gamma_{l\alpha}}\left[1-\frac{1}{1+(i\omega\tau_l)^{C_l}\frac{\gamma_{l\alpha}}{2\bar{a}_l\lambda_{l\alpha}}}\right]\}^{-1}, \quad (1)$$

where ρ_0 is the matrix resistivity, e is the ellipticity of the grains, and f is their volume fraction. Parameters τ and C are similar to the Cole-Cole model and represent the time constant and relaxation parameter, respectively. The constants $\bar{a}_l$ are the average values of the equatorial (a_{lx} and a_{ly}) and polar (a_{lz}) radii of the ellipsoidal grains. The coefficients $\gamma_{l\alpha}$ and $\lambda_{l\alpha}$ are the structural parameters defined by the geometrical characteristics of the ellipsoidal inclusions.

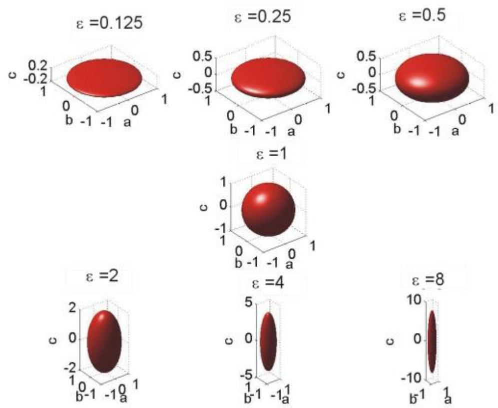

Figure 1: Typical rotational ellipsoids for different values of the ellipticity ε = c/a, the ranging from 0.125 to 8.

Inversion for the GEMTIP model parameters

An important question is how well the developed elliptical GEMTIP model could represent the actual complex resistivity of the rocks. In order to answer to this question, we formulate the inverse GEMTIP problem as follows. We introduce a vector, **m**, of the unknown model parameters,

$$\mathbf{m} = [\rho_0, e_1, \tau_1, C_1, f_1, e_2, \tau_2, C_2, f_2],$$

and a vector, **d**; of the observed data (the values of the complex resistivity as function of frequency):

$$\mathbf{d}=[\rho_e(\omega_1),\rho_e(\omega_2),\rho_e(\omega_3),\ldots\rho_e(\omega_n)].$$

Using these notations, we can write following expression for an inverse problem:

$$\mathbf{d} = A(\mathbf{m}) \quad (2)$$

where A is a forward modeling operator described by equation (1).

We solve equation (2) with respect to **m** by minimization of the following parametric functional:

$$P^\alpha(\mathbf{m}) = \|\mathbf{d} - A(\mathbf{m})\|^2 + \alpha\left\|\mathbf{W}_m\mathbf{m} - \mathbf{W}_m\mathbf{m}_{apr}\right\|^2 = \text{min}, \quad (3)$$

where α is a regularization parameter, $\mathbf{W}_m$ is the weighting matrix of the model parameters, and $\mathbf{m}_{apr}$ is some a priori model selected based on all available rock physics data for the rock sample under consideration (Zhdanov, 2002).There are different methods available for solving minimization problem (3). In our study, we have used a new hybrid method based on a genetic algorithm with simulated annealing (SAAGA), introduced by Lin et al. (2015).

QEMSCAN and GEMTIP analysis of the rock samples

We will present below the results of QEMSCAN and CR study for the rock samples from the Cu-Au deposit in Mongolia. The copper-gold ore is hosted in the hydrothermal alteration zone. The mineralization is a low-sulfide type. The distribution of the mineralization is uneven and it was determined that the mineralization is generally distributed in or vicinity of the quartz-carbonate gangue located inside of the hydrothermal alteration zone. Mineralization is associated with chalcopyrite related to early quartz veins. The main exploration problem in this case is the ability to differentiate between normally barren pyrite bearing alteration phases and mineralized chalcopyrite phases. Systems generally always have pyrite but not all are mineralized with Cu bearing sulphides. Discrimination between pyrite and chalcopyrite could be considered as an important application of the IP survey.

The mineralogical analyses of mineral and host rock samples were performed using the quantitative evaluation of minerals by scanning electron microscopy (QEMSCAN) system. QEMSCAN provides detailed particle mineralogical analysis including quantification of mineral proportions, average grain size for selected mineral, average grain density, estimated minerals fraction volume, etc.

The measurements of complex resistivity (CR) were conducted by a specialized system operating in frequency domain to avoid errors related to the conversion from time to frequency domain. The amplitudes and phases of the recorded signals were examined by a spectrum analyzer and converted to the real and imaginary parts of complex resistivity at each frequency. These individual CR measurements were then collated to form the complex resistivity (CR) spectrum of the sample. Additional experimenal details of the CR measurement system can be found in Burtman et al. (2010 and 2011).

Figure 2. A QEMSCan image of the rock sample #37 from Au-Cu deposit. The calcite and quartz are designated by dark and light pink colors, respectively, while dolomite is shown by blue, chalcopyrite by orange, and pyrite by yellow in this image.

Figures 2 and 3 present, as an example, the results of QEMSCan analysis for rock samples # 37, and 40. Note that, according to the QEMSCan results, the rock samples contain more than one type of mineral. The major sulfide minerals present in these samples are chalcopyrite and pyrite. Therefore in all these samples we consider the structure that contains two different mineral phases and host matrix phase, totally three phases. Thus the three-phase GEMTIP model was utilized for analysis of complex resistivity.

Sample #37 contains six minerals shown in Figure 2, with the major concentration of calcite and quartz. Sample #40 contains twelve minerals shown in Figure 3, with the major concentration of calcite and dolomite and also with 0.6% of pyrite and 0.38% of chalcopyrite.

Figures 4 and 5 present imaginary part of the complex resistivity spectra measured for the same samples. Remarkably that all complex resistivity curves show at least two inflection points in imaginary resistivity spectra. The corresponding GEMTIP parameters, produced by the inversion, are shown in the tables provided below.

The three phase GEMTIP analysis of Imaginary part of CR spectrum (Figures 4 and 5) of samples #37 and #40 demonstrates that GEMTIP model revels correctly the presence of two minerals, pyrite and chalcopyrite, in well agreement with QEMSCan analysis of these samples (Figures 2 and 3).

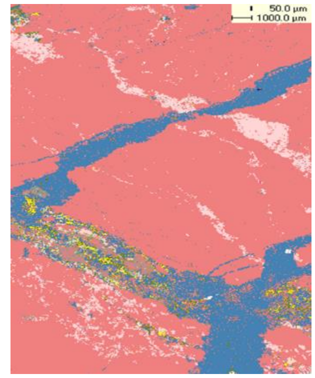

Figure 3. A QEMSCan image of the rock sample #40 from Au-Cu deposit. The calcite and quartz are designated by dark and light pink colors, respectively, while dolomite is shown by blue, chalcopyrite by orange, and pyrite by yellow in this image.

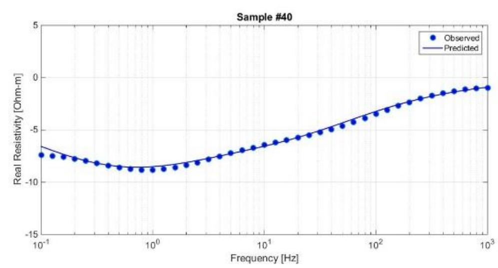

Figure 4. Imaginary part of the observed complex resistivity spectrum (blue dots) and the data predicted based on the GEMTIP model (black line) for the rock sample #37. The predicted data were obtained using three-phase GEMTIP model.

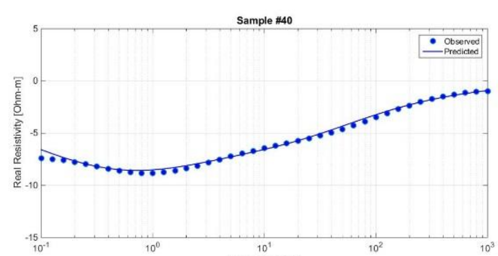

Figure 5. Imaginary part of the observed complex resistivity spectrum (blue dots) and the data predicted based on the GEMTIP model (black line) for the rock sample #40. The predicted data were obtained using three-phase GEMTIP model.

The GEMTIP analyses provide approximately the same values for relaxation coefficient for pyrite and for chalcopyrite grains, while chalcopyrite grains have larger time constant than pyrite grains. Therefore the lower frequency nonlinearity inflection points in Figures 4 and 5 are associated with chalcopyrite, while higher frequency increases at Figures 4 and 5 are associated with pyrite. Tables 1 and 2 summarize the results of GEMTIP inversion for rock samples #37, and #40. The recovered values of two different volume fractions of inclusions with different electrical properties were used for three-phase models.

Table 1: GEMTIP parameters recovered by inversion of CR spectrum for sample #37 from the Cu-Au deposit

Model Parameter	Units	Value
DC resistivity, ρ_0	ohm-m	600
grain 1-pyrite: fraction volume, f_1	%	0.125
grain 1-pyrite:relaxation coefficient, C_1	-	1
grain 1-pyrite:time constant, τ_1	sec	0.0053
grain 1-pyrite: ellipticity: e_1	-	10
grain 2-chalcopyrite: fraction volume, f_2	%	1.59
grain 2-chalcopyrite:relaxation coefficient, C_2	-	0.66
grain 2-chalcopyrite: time constant, τ_2	sec	1.52
grain 2-chalcopyrite :ellipticity: e_2	-	10

Table 2: GEMTIP parameters recovered by inversion of CR spectrum for sample #40 from Cu-Au deposit

Model Parameter	Units	Value
DC resistivity, ρ_0	ohm-m	405
grain 1-pyrite: fraction volume, f_1	%	3.6
grain 1-pyrite:relaxation coefficient, C_1	-	0.464
grain 1-pyrite:time constant, τ_1	sec	0.3
grain 1-pyrite: ellipticity: e_1	-	1.3
grain 2-pyrite: fraction volume, f_2	%	0.16
grain 2-pyrite:relaxation coefficient, C_2	-	0.6
grain 2-pyrite:time constant, τ_2	sec	0.013
grain 2-pyrite: ellipticity: e_2	-	10

Conclusion

We have demonstrated that the complex resistivity spectrum of the mineral rocks can be described by a three-phase GEMTIP model with elliptical inclusions. This model is a generalization of the classical Cole-Cole model, which appears in the special case of inclusions with spherical shape. The GEMTIP model provides analytical expressions connecting the effective electrical parameters of the rocks with the intrinsic petrophysical and geometrical characteristics of the composite medium: the mineralization of the rocks, the matrix composition, and the polarizability of the formations. The results of the QEMSCan mineralogical, complex resistivity (CR), and GEMTIP analysis of representative mineral rock samples collected from the Cu-Au deposit in Mongolia have shown that different types of mineralizations are characterized by different behaviors of the parameters of the GEMTIP model. These results open the possibility for mineral discrimination based on CR measurements.

Acknowledgements

The authors acknowledge the Consortium for Electromagnetic Modeling and Inversion (CEMI) and TechnoImaging for support of this research and permission to publish. We are thankful to First Eurasian Mining LC for providing the rock samples for the petrophysical analysis.

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