Electromagnetic modeling based on the rock physics description of the true complexity of rocks: applications to study of the IP effect in porphyry copper deposits

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SUMMARY

A new approach to EM forward modeling from the grain-scale to deposit-scale is presented using a porphyry copper system. The Generalized Effective Medium Theory of the induced polarization (GEMTIP) effect and electromagnetic (EM) field propagation in heterogenous polarizable media presented by Zhdanov (2006) allows the incorporation of rock-scale parameters such as mineralization and/or fluid content, matrix composition, porosity, anisotropy, and the polarizability of the formations. GEMTIP is used for rock-scale forward modeling from grain-scale parameters. Empirical data from rock-scale measurements (Ostrander and Zonge, 1978) are in good agreement with GEMTIP forward modeling output for pyrite and chalcopyrite bearing rocks. To further our understanding of IP on a larger scale, deposit-scale modeling is conducted for a porphyry system. A simplified porphyry model is created for future detectability and mineral discrimination studies.

INTRODUCTION

Traditionally, electromagnetic (EM) modeling has been based on geoelectrical models of geological targets (e.g., ore deposits or hydrocarbon reservoirs), which are characterized by some bulk conductivity distribution described by a real function of the spatial coordinates. It is also usually assumed that the conductivity is time and/or frequency independent. However, the actual conductivity of geological formations is defined by the complex microscopic and macroscopic heterogeneous structures of minerals and rocks with different petrophysical properties. This intrinsic complexity of the internal structure of the rocks may result in complex values of the bulk conductivity. Moreover, this complexity may give rise to frequency and/or time dependence of the rock's conductivity, which is manifested through induced polarization (IP) effects.

In this paper we develop an approach to constructing a new generation of EM modeling software which would take into account the true complexity of the rocks. Our approach is based on the rock physics description of the medium as a composite heterogeneous multiphase formation. We use a generalized effective medium representation, developed by Zhdanov, 2006, to generate effective conductivity models of an ore deposit. Our new formulation of a geoelectrical model takes into account the mineralization and/or fluid content of the rocks and the matrix composition, porosity, anisotropy, and polarizability of the formations. This approach will allow us to provide a link between the volume content of the different minerals and the observed electromagnetic (EM) field data.

The new Generalized Effective Medium Theory of IP (GEMTIP) provides a unified mathematical model of the heterogeneity, multiphase structure, and polarizability of the rocks. It takes into account both electromagnetic induction (EMI) and induced polarization (IP) effects related to the relaxation of polarized charges in rock formations.

The development of the IP method can be traced back to the 1950s, when both mining and petroleum companies were actively looking into the application of this method to mineral exploration. The physical-mathematical principles of the IP effect were originally formulated in pioneering works by Wait (1959) and Sheinman (1969). However, this method did not find wide application in US industry until after the work of Zonge and his associates at the Zonge Engineering and Research Organization (Zonge and Wynn, 1975) and Pelton et al (1978) at the University of Utah. Significant contribution to the development of the IP method was made, also, by Wait (1959, 1982), and by the research team at Kennecott in 1965-1977 (Nelson, 1997). The IP method has found wide application in mining exploration. A number of successful applications of the IP method in hydrocarbon exploration were reported by Russian and American geophysicists (e.g. Komarov, 1980; Zonge, 1983; Kamenetsky, 1997; Davydycheva et al, 2004) as well. The new Generalized Effective Medium Theory of IP (Zhdanov, 2006) offers an expansion of rock properties included over preexisting models such as the widely accepted Cole-Cole model (Cole and Cole, 1941).

In this paper we will consider rock formations typical for an ore deposit. A simplified model of a typical porphyry copper system in the southwestern U. S. is developed for the purpose of EM response evaluation. The porphyry system is modeled on both the rock-scale and the deposit-scale. A comparison between GEMTIP and the empirical measurements conducted by Ostrander and Zonge (1978) is presented for rocks containing disseminated sulfides.

EFFECTIVE RESISTIVITY MODEL

Generalized Effective Medium Theory allows the spectral behavior of rock conductivity to be predicted based on its composition at the grain-scale. The first step is to construct a simplified model of the rock similar to the example in Figure 1. This example has two minerals contained in a matrix. While the theory holds for all grain shapes, in this paper we will use spherical grains in a matrix. Future implementations will allow for ellipsoidal and other grain shapes to be modeled. Upon simplification of the rock sample a geologic assessment is conducted for grain types, grain radii, grain eccentricity (ellipsoidal case), and volume percent. Grain conductivity, the surface polarizability coefficient, and the relaxation coefficient must be established by lab measurements for each phase of interest. The effective resistivity of the polarized inhomogeneous medium composed of a matrix with *l* types of spherical grains is given by equation (1):

$$\rho_{ef} = \rho_0 \left\{ 1 + \sum_{l=1}^{N} \left\{ f_l m_l \left\{ 1 - \frac{1}{1 + \{i\omega\tau_l\}^{C_l}} \right\} \right\} \right\}^{-1}, \qquad (1)$$

where:

$$m_l = 3\frac{\rho_0 - \rho_l}{2\rho_l + \rho_0} \text{ and } \tau_l = \left\{ \frac{a_l}{2\alpha_0} \{2\rho_l + \rho_0\} \right\}^{1/C_l}. \qquad (2)$$

Table 1 provides a full explanation of each parameter. The additional capabilities of GEMTIP allow for more accurate forward modeling and could open the door to better mineral discrimination in future (Zhdanov, 2006).

PORPHYRY SYSTEM OVERVIEW

Porphyry systems are important geologic targets for mineral exploration. For this reason the development of a simplified porphyry model was accomplished for future tests of detectability, the effects of nearby geologic structures, and optimal survey design. For modeling purposes a simplified porphyry model was constructed based on known geologic information (Titley, 1982, and Pierce, 1995) and provided geoelectric

variable	units	name	description
ρ_{ef}	Ohm-m	effective resistivity	resulting effective resistivity
ρ_0	Ohm-m	matrix resistivity	matrix resistivity of rock being modeled
f_l	-	grain volume fraction	volume fraction of each grain type
m_l	-	grain chargeability	grain chargeability of each grain type
ω	Hertz	angular frequency	angular frequency of EM signal
τ_l	second	time constant	time constant for each grain
C_l	-	decay coefficient	decay coefficient determined from empirical data
ρ_l	Ohm-m	grain resistivity	resistivity of each grain type
a_l	meter	grain radius	radius of each grain type
α_0	$\frac{\text{Ohm}\cdot\text{m}^2}{\text{sec}^{c_l}}$	surface polarizability coefficient	behavior of charges on grain surface determined from empirical data

Table 1: GEMTIP parameter overview.

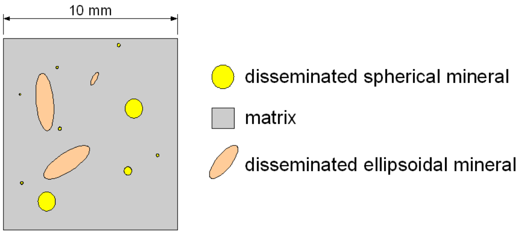

Figure 1: Simplified illustration of disseminated mineralization for modeling. This figure illustrates the basic geometrical input parameters for modeling with GEMTIP including grain size, grain eccentricity (if using an ellipsoidal model) and matrix. It should be noted that any number of minerals could be included. Additional information on geoelectrical input parameters can be found in Table 1.

values (J. Inman, pers. commun.). This model is characterized by potentially strong EM coupling as well as IP effects. The simplified porphyry model, shown in Figure 2, incorporates the classic zones seen in many porphyry deposits including supergene zones: leached cap, enriched zone and the unweathered zones: pyrite shell, chalcopyrite (ore zone), and barren core of the intrusion. A normal fault was also included near the deposit. With a better understanding of the deposit-scale of a porphyry system the rock-scale is investigated.

ROCK-SCALE MODELING OF PORPHYRY SYSTEM ROCKS

Rock-scale modeling is conducted for two porphyry deposit rocks. Bingham chalcopyrite ore and Silver Bell pyrite/chalcopyrite ore. Figure 3 shows the disseminated nature of the chalcopyrite grains in a quartz monzonite (QMP) matrix for the Bingham chalcopyrite ore. Disseminated pyrite and chalcopyrite are present in the Silver Bell ore. The disseminated grains are treated as spheres for the purpose of modeling. A detailed listing of parameters used for forward modeling of the Bingham and Silver Bell ore is provided in Table 2. The behavior of effective resistivity computed by GEMTIP over a broad range of frequencies for the two ores is shown in Figure 4. The lower frequency and greater magnitude of the pyrite containing Silver Bell IP response is consistent with the literature (Pelton et al, 1978).

A fit of GEMTIP prestitcted data with empirical measurements of Ostrander and Zonge's 1978 study of chalcopyrite and pyrite bearing synthetic rocks with known matrix resistivities was conducted. For Ostrander and Zonge's study, rocks bearing either pyrite or chalcopyrite at specific grain sizes were constructed using a cement (matrix) of known resistivity. After the construction of each rock, the frequency of the peak IP response was measured. Results from this study are plotted as the solid squares and solid triangles in Figure 5. The grey shading is used to indicate the range of grain sizes for each measurement of maximum IP response, for example the pyrite synthetic rock plotted at 2.5 mm contains pyrite grains from 2 mm to 3 mm. After a quick experimentation with the values of the surface polarizability coefficient and relaxation coefficient for each mineral type a good correlation between GEMTIP and Ostrander and Zonge (1978) was established (see Figure 5). These results are exciting and encouraging although more testing must be conducted. In the future, application of our knowledge gained on the rock scale will be important for forward modeling and inversion on the deposit scale.

DEPOSIT-SCALE MODELING OF A PORPHYRY SYSTEM

After an investigation of the rock-scale, deposit-scale modeling of a porphyry system is accomplished. The CEMI Integral Equation (IE) forward modeling code IBCEM3DIP is used to conduct the forward modeling (Zhdanov and Lee, 2005). A synthetic 2-D dipole dipole survey was constructed. N spacing is 200 m along a 5000 m line centered over the ore body shown in 6. Survey frequencies of 0.125, 0.5, 1, 4, 8, and 16 Hz were used. The clear apparent resistivity anomaly in Figure 7 shows the conductive overburden does not hide the 150 meter deep, 80 meter thick, highly conductive enriched zone. This forward model might provide an analog to the gravel buried porphyries of El Salvador. The nearby fault produces a slight apparent resistivity anomaly in the left of Figure 7. Interestingly and fortunately it does not produce a significant phase anomaly as shown by Figure 8. This has important implications for exploration where a DC resistivity anomaly may mask an ore body making the phase response important to the interpretation, indicating the importance of understanding the IP effect of the ore body and surrounding geology.

CONCLUSIONS AND FUTURE WORK

Recent developments in IP theory and forward modeling have opened the door to further our understanding the IP effect in both mineral and petroleum exploration leading to better detection and discrimination capabilities. The development of GEMTIP now allows the inclusion of rock-scale parameters such as mineralization and/or fluid content, matrix composition, porosity, anisotropy, and the polarizability of the formations. The capability to model the IP effect on rock-scale has been developed. Initial testing shows GEMTIP producing comparable results to empirical data. As with any new idea additional comparisons will be necessary to test the robustness of the GEMTIP model. To further understand an important mineral exploration target a simplified porphyry model was created for forward modeling with the IBCEM3DIP code. Additional study of survey design implications and detectability can be easily conducted with the new simple porphyry model and code.

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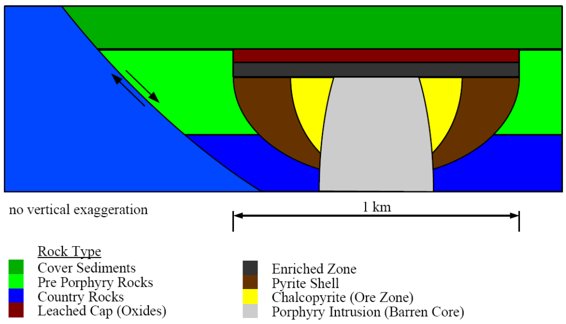

Figure 2: Simple porphyry model. Above is a simplified porphyry model that can be easily modeled using CEMI IE codes. This model incorporates the classic zones of a porphyry deposit and a normal fault.

variable	Bingham	Silver Bell
ρ_{QMP}	200 Ohm-m	200 Ohm-m
$f_{chalcopyrite}$	5	7.5
f_{pyrite}	-	7.5
ω	10^{-2} to 10^{6}	10^{-2} to 10^{6}
$C_{chalcopyrite}$	0.5	0.5
C_{pyrite}	-	0.5
$\rho_{chalcopyrite}$	0.004 Ohm-m[a]	0.004 Ohm-m
ρ_{pyrite}	-	0.3 Ohm-m[a]
$a_{chalcopyrite}$	0.5 mm	0.5 mm
a_{pyrite}	-	0.5 mm
α_0	0.85	0.68

[a] Nabighian, 1988

Table 2: GEMTIP parameters for Bingham and Silver Bell ore modeling

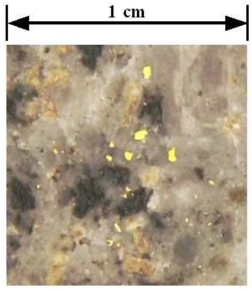

Figure 3: Bingham chalcopyrite ore. This close up photograph illustrates the disseminated nature of the chalcopyrite.

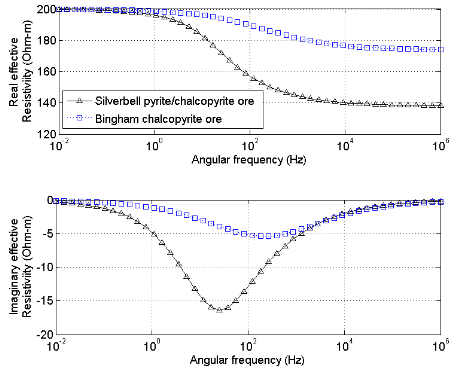

Figure 4: Spectral response of Bingham and Silver Bell ores from GEMTIP. Effective resistivity is plotted as a function of frequency for each rock sample.

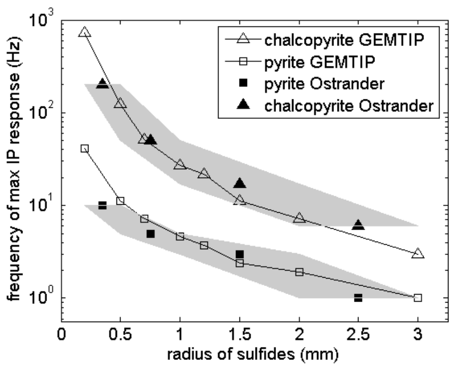

Figure 5: Fit of GEMTIP to empirical data. The results from Ostrander and Zonge (1978) are plotted as filled symbols. The grey shading indicates the range of disseminated sulfide grain size used for each measurement. Results from GEMTIP are plotted using the solid line and open symbols.

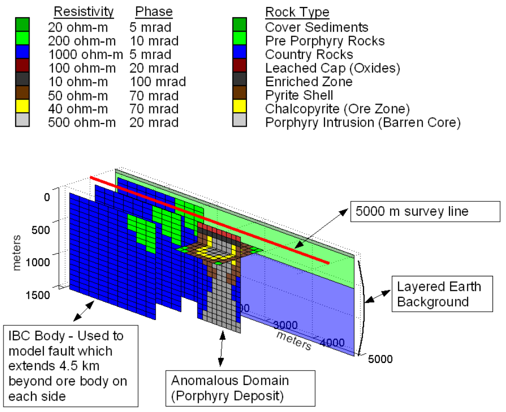

Figure 6: MATLAB porphyry forward model. The above diagram depicts the anomalous domain, the location of the survey line, the layered earth background, and the IBC body for a forward modeling run performed in MATLAB using IBCEM3DIP. The enriched zone is 80 meters thick and 150 meters deep.

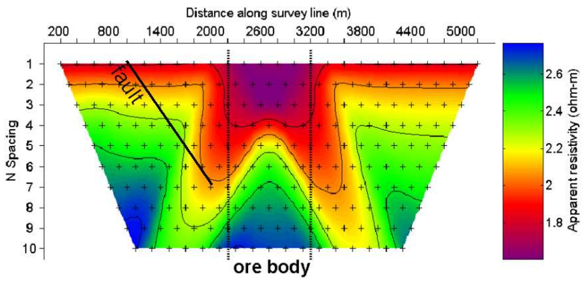

Figure 7: Apparent resistivity pseudosection for 1 Hz data. A conductivity anomaly surrounds the ore body in the center. Influence of the fault is seen in the right side of the psuedosection where the apparent resistivity is higher and creates asymmetry in the response produced by the ore body.

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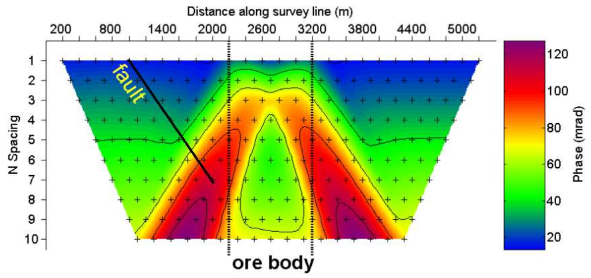

Figure 8: Apparent phase pseudosection for 1 Hz data. A phase anomaly due to the ore body is symmetric about the center. Influence of the fault is not seen in the phase data as it does not have a strong IP response.

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