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Induced polarization with in-loop transient electromagnetic soundings: A case study of mineral discrimination at El Arco porphyry copper, Mexico

Carlos Flores *, Sergio A. Peralta-Ortega [1]

Departamento de Geofísica Aplicada. Centro de Investigación Científica y Educación Superior de Ensenada (CICESE), km. 107 Carretera Tijuana-Ensenada, Ensenada, Baja California, México

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ABSTRACT

With the inversion of in-loop transient electromagnetic (TEM) soundings over the El Arco porphyry copper deposit in terms of one-dimensional Cole–Cole dispersive models we found that the relationship between the chargeabilities and the time constants shows a fair agreement with the actual mineral concentrations measured in drillhole cores. This is the first reported case of mineral discrimination with this technique. Through a sensitivity analysis we show that these two parameters are the least well resolved.

1. Introduction

The induced polarization (IP) method has been shown to be an effective tool in mineral exploration (Fink et al., 1990). In most IP studies the data are acquired with ground electrodes, most commonly with the dipole–dipole configuration. A current is introduced into the ground through two current electrodes, and a potential difference is measured between two potential electrodes located at some distance from the current electrodes. The polarization of the subsurface can be detected in two domains. In the time domain, the decaying voltage is measured at several times after a dc current is interrupted. In the frequency domain, the voltage and its phase shift are measured for different frequencies of a sinusoidal applied current.

An alternative to the current-injection or galvanic IP approach is the use of a purely inductive technique, such as the transient electromagnetic (TEM) sounding in the in-loop or coincident-loop configurations (Spies and Frischknecht, 1991; Nabighian and Macnae, 1991). The presence of polarizable material usually manifests in these data as a change of sign in the measured voltages followed by the decay of the negative voltages. Gubatyenko and Tikshayev (1979) and Weidelt (1982) theoretically showed that for the coincident-loop configuration these sign reversals cannot occur in a frequency-independent linear medium, attributing them to polarization effects. In the in-loop array a similar effect is expected when the ground is quasi-layered. In the TEM in-loop configuration, a sounding is carried out with a large rectangular or square transmitting loop and a horizontal coil located at the center of the loop. The injected dc current in the loop is periodically interrupted in the form of a linear ramp. An induced current system, flowing in closed paths below the loop, is created each time the transmitter current is interrupted, producing a secondary magnetic field. The time variation of the vertical component of this magnetic field induces a voltage at the receiver coil. In the presence of polarizable rocks a polarization current with opposite direction to that of the fundamental induction current is also created (Smith and West, 1988). These current systems usually decay at different rates. The decay rate of the polarization current is usually slower, such that in late-times the negative polarization current may be greater than the positive fundamental induced current, producing the sign reversal in the measured voltages. As the spatial and temporal distribution of the subsurface current system depends upon the ground resistivity, the measured transient voltage gives information about the subsurface resistivity. The locus of the maximum amplitude of the induced currents diffuses downward and outward with time, thereby giving information about deeper regions as time increases (Nabighian, 1979; Hoversten and Morrison, 1982).

Pelton et al. (1978) and Vanhala and Peltoniemi (1992) carried out galvanic spectral IP measurements over many mineralized outcrops with known mineral concentrations and textures. By inverting their measurements to homogeneous Cole–Cole dispersive models, they found that the relationship between two Cole–Cole parameters (chargeability and time constant) gives information on the mineral concentration and textures, an ability known as mineral discrimination. Despite the fact that in-loop TEM soundings are also sensitive to polarizable material, still there has not been any published field case showing that it is possible to do mineral discrimination with the TEM method. In this paper we present a field case of mineral discrimination where the inversion of in-loop TEM responses to 1D dispersive models

* Corresponding author. Tel.: +646 1750500x26326; fax: +646 1750567.
E-mail addresses: cflores@cicese.mx (C. Flores), sortega2@villahermosa.oilfield.slb.com (S.A. Peralta-Ortega).
[1] Now at: Schlumberger Oilfield Services. Km. 7 Carretera Villahermosa-Cárdenas, Ranchería Lázaro Cárdenas, Villahermosa, Tabasco, México.

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over a porphyry copper deposit shows a reasonable agreement with the drilling information on sulfide concentrations (Peralta-Ortega, 2001).

1.1. The IP effect on TEM soundings with a Cole–Cole model

The dispersive character of the IP phenomena is usually described with the Cole–Cole model (Cole and Cole, 1941; Pelton et al., 1978; Lee, 1981; Vanhala and Peltoniemi, 1992; Ghorbani et al., 2007)

$$\rho(\omega) = \rho_0\left[1 - m\left(1 - \frac{1}{1 + (i\omega\tau)^c}\right)\right] \quad (1)$$

where ρ_0 is the zero frequency or direct current resistivity (Ωm), m is the chargeability (dimensionless), τ is the time constant (seconds), and c is the frequency exponent (dimensionless). The four parameters have different ranges of variation. The chargeability and the frequency exponent can vary from 0 to 1. The dc resistivity and the time constant have wide ranges, from 10^{-2} to 10^5 Ωm and from 10^{-5} to 10^4 s, respectively.

Fig. 1 shows the amplitude and phase spectra of the Cole–Cole model. Each graph displays the behavior of the dispersive resistivity (expression (1)) when only one parameter of the reference model [100, 0.5, 0.01, 0.5] is varied, keeping the other three fixed. We will be using the notation [ρ_0,m,τ,c] for defining the four Cole–Cole parameters of a homogeneous medium. Solid lines are used for the amplitudes and dashed lines for the phases, which are all negative. The effects of varying the parameters are different. Varying the dc resistivity affects the amplitudes but not the phases (Fig. 1a). The variation of the chargeability from 0.1 to 0.9 has a profound effect; the amplitudes show a sharp decrease for high frequencies and the phases increase (Fig. 1b). Increasing the time constant from 10^{-4} to 1 shifts the amplitudes and phases toward low frequencies (Fig. 1c), while increasing the frequency exponent sharpens the amplitude and phase spectra (Fig. 1d).

The effect of varying the Cole–Cole parameters on the in-loop voltages of a TEM sounding is shown in Fig. 2. The transmitter and receiver parameters used in this numerical simulation are representative of those employed in El Arco field survey. The four drawings of Fig. 2 result from varying one parameter at a time of the same reference model [100,0.5,0.01,0.5] of Fig. 1. The most diagnostic feature of the IP cases is the sign reversal, the peaking of the negative voltages (dashed lines), followed by a decay. We include the noise level found in El Arco, which is about 1×10^{-8} V. Increasing the dc resistivity to 1000 Ωm (Fig. 2a) shifts the sign reversal to earlier times and increases the negative peak, while decreasing it to 10 Ωm causes the opposite effect. For comparison, Fig. 2a also shows the voltages of a non-polarizable homogeneous medium of 100 Ωm, characterized by all-positive voltages. Varying the chargeability (Fig. 2b) has a similar effect to the variation of the dc resistivity. Notice, however, that the sign reversal for $m = 0.1$ occurs well below the noise level, such that for this case the IP effect might not be recognized by the interpreter. The increase of the time constant (Fig. 2c) and the frequency exponent (Fig. 2d) also produce shifts of the sign reversal toward earlier times. The case for $\tau = 10^{-4}$ s does not produce the sign reversal within the calculated time window, and for $c = 0.25$ the sign reversal is slightly below the noise level. These are examples of the difficulty of recognizing the IP effect for several combinations of parameters.

The importance of the Cole–Cole model stems on its ability to do mineral discrimination, i.e., to perform semi quantitative inferences on the concentration and size of the metallic minerals in a mineral deposit, which is a very useful interpretation tool in mining prospecting. Pelton et al. (1978), in a cornerstone geophysical work, carried out variable-frequency voltage measurements with the dipole–dipole array over several mineral outcrops in the United States and Canada. By inverting

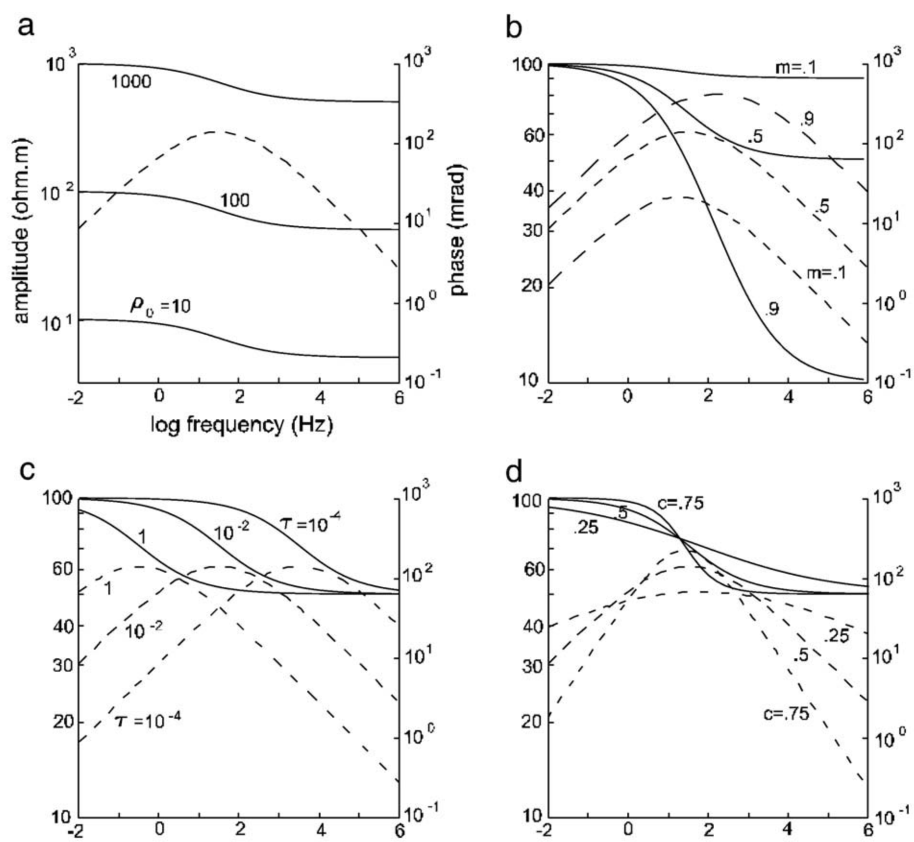

Fig. 1. Amplitude (solid lines) and phase (dashed lines) spectra of the Cole–Cole relaxation model. a) Varying the dc resistivity, b) the chargeability, c) the time constant, and d) the frequency exponent of the reference model [$\rho_0 = 100$, $m = 0.5$, $\tau = 0.01$, $c = 0.5$].