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Time domain spectral induced polarization of disseminated electronic conductors: Laboratory data analysis through the Debye decomposition approach

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ABSTRACT

We measured Spectral Induced Polarization responses of 22 models of disseminated ore with a time domain (TD) technique. The models were mixtures of calibrated sand (0.2–0.3 mm) with calibrated ore grains (average radii: 0.045, 0.055, 0.13, 0.20, 0.38 and 0.55 mm). The grains represent a mixture of pyrrhotite (30%), pyrite (30%), magnetite (30%) and chalcopyrite (10%) coming from a natural ore. In the models, the grain concentration (by volume) varied between 0.6 and 30%.

We obtained IP decays with a conventional field TD measuring technique and a lab low-current transmitter in the time range from 0.3 ms to 64 s. The IP decays measured with various current wavelength forms were inverted to relaxation time distributions (RTD) on the basis of the Debye decomposition approach.

RTD parameters were found to be closely related to the ore volumetric content and the ore grain size. The total chargeability is independent of the grain size, but is determined by the grain volume fraction. In contrast, the mean IP relaxation time is related to the grain size. These facts make RTD attractive to use in ore prospecting and studying reactive permeable barriers.

Moreover, for low salinity pore water used in this study, the relaxation times of disseminated ores are three to four decades smaller than that of the insulating grains of the same size typical of common soils and sediments. This allows recover the relaxation times on the basis of relatively fast IP measurements with short time pulses (in TD) or high frequency values in the frequency domain; however attention should be paid to inductive and capacitive couplings.

1. Introduction

In the last decades, there is a growing interest in the use of the Induced Polarization (IP) method mainly in hydrogeology and environmental geology. This produced strong development of field technique and data interpretation methodology, improved factual databases, as well as stimulated development of a spectral IP (SIP) approach, when IP parameters are investigated through large frequency (or time) ranges. One of the latest developments was a so-called Debye decomposition (DD) technique (Nordsiek and Weller, 2008; Tarasov and Titov, 2007; Tong et al., 2006; Zisser et al., 2010), which allows obtaining a relaxation time distribution (RTD). The relaxation time distribution characterizes polarization magnitude as a function of its characteristic relaxation time. It was shown that SIP is a powerful tool for discriminating the pore or grain size in soils and sediments, and, so, for predicting their texture parameters, like the specific surface (e.g., Slater et al., 2005, 2006; Weller et al., 2010) and, possibly, the hydraulic conductivity (e.g., Revil et al., 2012).

Recent experimental researches were mainly focused on soils and sediments. Only few datasets concerning disseminated electronic conductors or semiconductors (which we call thereafter as 'metallic particles') were obtained in the framework of monitoring reactive permeable barriers (Slater et al., 2005, 2006), environmental applications (Ntarlagiannis et al., 2010; Placencia-Gómez et al., 2013), and investigations of archaeological objects (Florsch et al., 2011, 2012).

However IP is traditionally used in mining geology for disseminated ore prospecting (e.g., Nelson and Van Voorhis, 1983; Pelton et al., 1978; Scott and West, 1969; Seigel et al., 1997; Vanhala and Peltoniemi, 1992). In the past decade the current prices of rare metals (precious or noble, and, especially, gold) have continuously increased. Gold is very frequently accompanied by disseminated sulfide minerals like pyrite and

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arsenopyrite, and IP anomalies are traditionally considered as gold deposits indications (e.g., Andreev, 1992; Hofstra and Cline, 2000). However to the best of our knowledge the DD technique has been used to study disseminated metallic particles in two recent papers only and has been applied to limited datasets (Nordsiek and Weller, 2008; Placencia-Gómez et al., 2013).

In this paper we systematically apply the DD technique to new laboratory data obtained in models of disseminated ore. The models were mixtures of sand and metallic particles of different mass content and grain size. We compared RTD-derived parameters with traditional IP parameters like the chargeability, and we show advantages in the use of the RTD technique in study disseminated metallic particles.

2. Induced Polarization fundamentals

Induced Polarization of porous media is a synonym of the low-frequency dispersion of electrical conductivity. This means that the electrical conductivity is a complex quantity, which depends on the value of electrical field frequency. This definition is directly used in a so called Frequency Domain (FD) when the electrical conductivity (or its inverse, the resistivity) is measured in a wide frequency range (over 9 decades, from 1 mHz to 1 MHz, in laboratory conditions, and over 3 decades, from 0.1 to 100 Hz, in field conditions). In FD a couple of parameters (1) the real and imaginary components of electrical conductivity (resistivity) or (2) its absolute value and phase are used.

The imaginary conductivity value, σ'', represents the magnitude of induced polarization (e.g., Lesmes and Frye, 2001). The phase angle,

$$\varphi = \tan^{-1}\frac{\sigma''}{\sigma'} \approx \frac{\sigma''}{\sigma'}, \tag{1}$$

depends on both the polarization magnitude and the conduction magnitude σ'. In field measurements the common FD parameter is also the frequency effect,

$$FE = \frac{\sigma(f_1) - \sigma(f_0)}{\sigma(f_0)}, \tag{2}$$

which can be considered as a 'local' measure of the conductivity variation in the frequency range from f_0 to f_1.

IP is also manifested by a specific behavior, when the electrical field is a sequence of rectangular impulses. An electrical voltage in response to application of a rectangular current pulse is an increased function of time (Fig. 1). After the pulse end (when the current is turned off, the off-time) the voltage first decreases instantaneously, and, then decays slowly. This IP manifestation is directly used in a so called Time Domain (TD) technique, which is frequently applied in field conditions especially in mining applications. In TD, the polarizability (see Fig. 1) calculated on the basis of the voltages in the off-time, $U(t)$, and at the end of the on-time, U_0 (Komarov, 1980; Wait, 1982),

$$\eta(t) = \frac{U(t)}{U_0}, \tag{3}$$

is frequently used. Its average through the off-time between two pulses, the chargeability,

$$m = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} \eta(t)dt, \tag{4}$$

is defined as IP field integral parameter (e.g., Lesmes and Frye, 2001).

The proportionality between the complex conductivity phase, the frequency effect and the chargeability is well established theoretically and experimentally (Marshall and Madden, 1959; Seigel, 1959; Vinegar and Waxman, 1984; Wait, 1982). These parameters are measures of the ratio of the capacitive to conductive properties of materials (Lesmes and Frye, 2001). In contrast, σ'' is a direct measure of the capacitance of materials. Its TD analogical parameter is a normalized chargeability,

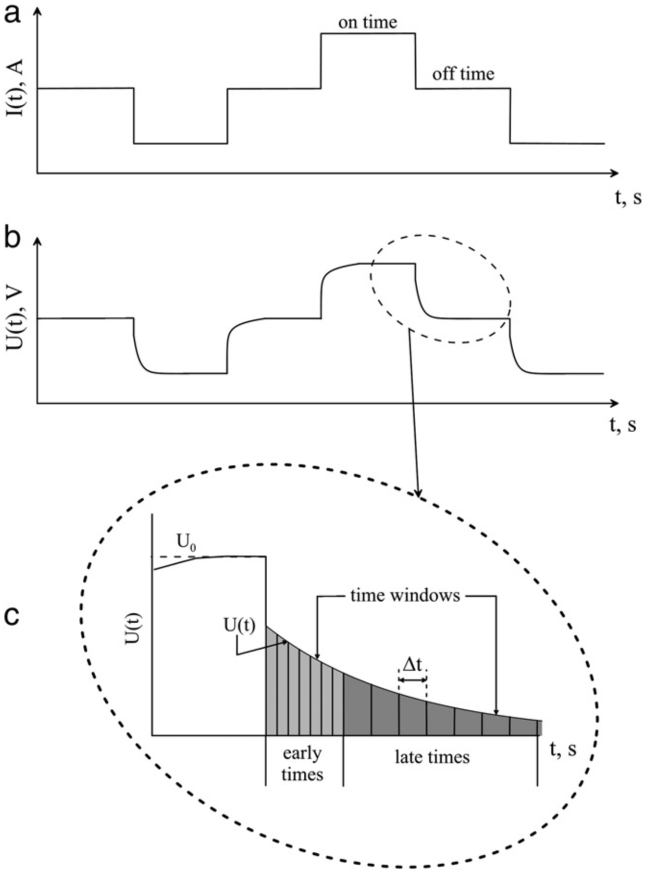

Fig. 1. Induced polarization in the time domain. a—current pulses; b—electrical voltage response to the current; c—sketch of the time domain IP measurements.

$$m_n = \frac{m}{\rho}. \tag{5}$$

where ρ is the electrical resistivity value. Note, like the conductivity, the normalized chargeability is measured in Siemens per meter, and in sediments it is tightly related to the surface conductivity (e.g., Lesmes and Frye, 2001; Slater and Lesmes, 2002).

Induced Polarization decays are not easy to compare because they are monotonous decreasing function. This is because a differential polarizability, a decay derivative with respect to the time logarithm,

$$\eta_d(t) = \frac{d\eta(t)}{d(\log(t))}, \tag{6}$$

was proposed (Komarov, 1980) and frequently used in Russia (see, e.g., Titov et al., 2002, 2005). In contrast to monotonous decays, the differential polarizability contains maximum at the time value close to the value inverse of the critical frequency in FD. A shape of differential polarizability vs. inverse of time is similar to that of the phase angle vs. frequency in FD.

3. Induced Polarization of sand–ore mixtures

Last decade great progress was achieved in understanding IP of soils and sediments. Existing models are mostly based on a theory of polarization of colloidal particle with electrical double (or triple) layer developed in colloidal sciences (Schurr, 1964; Schwarz, 1962), and applied to