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Transient characteristics of induced polarization in inhomogeneous media (*from results of 2D numerical simulation*)

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Abstract

This paper presents the results of 2D mathematical modeling of induced polarization (IP) in the cases of profiling and electrical tomography for piecewise homogeneous media containing ore bodies with different structures, sizes, depths, relaxation times, chargeability, and electrical resistivity. The standard and spectral approaches to data analysis are compared. The cases where analysis of transient IP characteristics yields new information of practical importance are considered. The main features of transient IP characteristics in 2D inhomogeneous media are determined from the modeling results. Analysis of transient IP characteristics is found to yield the best results when the depth of occurrence of polarizable bodies is minimal and their electrical conductivity is an order of magnitude lower than that of the host tock.

Keywords: induced polarization; mathematical modeling; relaxation time; chargeability; disseminated ores

Introduction

The induced polarization (IP) method is widely used to solve various geological, hydrogeological, environmental, archaeological, and other problems (Florsch et al., 2012; Kemna et al., 2012; Kirsch, 2006; Luo and Zhang, 1998; Pelton et al., 1978; and others). The most important advantage of the IP method over the resistivity method is that its parameters are related to the petrophysical properties of rocks that have little effect on their electrical resistivity. This makes it possible to evaluate rock properties of practical importance, such as the volumetric content of electronically conductive mineral grains, their dominant size, the dominant size of pores or grains of dielectrics, clay content, filtration coefficient, etc. (Gurin et al., 2015; Kemna et al., 2012; Mahan et al., 1986; Pelton et al., 1978; Revil and Florsch, 2010; Vanhala and Peltoniemi, 1992; Zisser et al., 2010; and others). In simple cases, these properties can be qualitatively estimated using standard methods for handling and processing IP data (determining the apparent polarizability or chargeability, phase angle, etc.). However, analysis of the time-domain (transient) or frequency-domain characteristics of IP can significantly improve the accuracy of estimates and in some cases, provide new information. This is due to the fact that the parameters characterizing the intensity of IP processes (total chargeability ore (M)) and their rate (relaxation time (τ)) are general independent of each other (Gurin et al., 2015). Therefore, when using standard approaches to the analysis of IP data, some information can be lost.

The first studies of the transient and frequency-domain characteristics of IP date back to the late 1960–early 1970s (Gennadinik et al., 1971; Komarov, 1965, 1972; Kormil'tsev and Mezentsev, 1989; Marshall and Madden, 1959; Postel'nikov, 1964; Shapovalov, 1972; Sheinman, 1969; and others). These studies have shown that the relaxation time of IP is related to the grain size of electronically conductive minerals. This suggested that the information capacity of the method can be significantly improved in some cases by analyzing the transient characteristics of IP (Gennadinik et al., 1971; Komarov, 1972; Shapovalov, 1972; Zonge and Wynn, 1975; and others). In particular, it was proposed to use the established relations between the relaxation time and the grain size of electronically conductive minerals to solve various survey and mapping problems. These include the classification of rocks into massive, veinlet, and disseminated types, according to the type of distribution of electronically conductive minerals. In addition, the idea was put forward to differentiate between the IP anomalies caused by graphitized rocks and sulfide mineralization (Karasev et al., 1973; Komarov, 1980;

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Kormil'tsev, 1980; Pelton et al., 1978; Shapovalov et al., 1976; Shereshevskii and Litmanovich, 1983; Sigel et al., 1997). At present, these ideas are still relevant. However, recent research efforts have focused on the solution of engineering, hydrogeological, and environmental problems rather than geological exploration (prospecting) problems. There are an increasing number of studies in which the above problems have been solved using not only the chargeability and electrical resistivity, but also other parameters: the relaxation time, the exponent in the Cole–Cole formula, etc. (Fiandaca et al., 2012, 2013; Gazoty et al., 2012; Kemna et al., 2012; and others). However, there are much less studies that have used these methods of IP data analysis to solve exploration problems.

Most of the recently published papers dealing with the analysis of the transient or frequency characteristics of IP are devoted to the results of laboratory work and the algorithms used to solve inverse IP problems in 1D, 2D, and 3D spaces. These algorithms are usually tested on relatively simple models in which inhomogeneities are represented by one or two prisms (Fiandaca et al., 2012; Loke et al., 2006; Oldenburg and Yaoguo, 1994; Routh et al., 1998). Despite the different approaches to solving the inverse problems, test examples show that they all provide highly accurate estimates of the true parameters of polarizable bodies. The most widely used models are those which contain near-surface bodies (the exploration depth is the first tens of meters). This is due to the fact that most researchers have addressed engineering-hydrogeological and ecological problems dealing with the upper geological section.

In geological explorations, the exploration depths are a few hundred meters, the exploration targets (mineralized zones or bodies) have a more complex structure with variable sulfide distribution (veinlet, disseminated, etc.), grain size, volume content, etc. Thus, more complex models are required to evaluate the applicability and informativeness of transient IP characteristics during IP exploration in various geological settings.

To identify the main difficulties and evaluate the possibilities of using characteristics IP transient in exploration and mapping, it is necessary to perform mathematical modeling.

Analysis of the literature shows that studies of transient IP characteristics using mathematical models of simple horizontally layered and piecewise homogeneous media are scanty (Gennadinik, 1971; Guptasarma, 1983; Liu and Vozoff, 1985; Luo and Zhang, 1998; Pelton et al., 1978; Soininen, 1984, 1985; and others).

Soininen (1984, 1985) compared apparent spectra of complex electrical resistivity ($\rho_a^*(\omega)$) and reference spectra ($\rho^*(\omega)$) using mathematical modeling of profiling data with various geoelectrical arrays over prisms embedded in a homogeneous half-space. To analyze the frequency characteristics of the IP, he used the Cole–Cole model (formulated by Pelton for resistivity (Pelton et al., 1978)). His papers contain a number of practically important conclusions. It has been found that the exponent in the Cole–Cole model (c) and the relaxation time (τ) can be estimated from $\rho_a^*(\omega)$ with sufficient accuracy for different geoelectrical arrays regardless of the shape of the polarizable body (for the geoelectric model containing one body). Consequently, the shape of spectra of $\rho^*(\omega)$ is well reproduced based on $\rho_a^*(\omega)$ (Soininen, 1984, 1985). In addition, simulations over two prisms with different Cole–Cole model parameters have shown that they can be reliably identified from spectra of $\rho_a^*(\omega)$ even if the difference in the time constant between them is small and is one decade (Soininen, 1985). Soininen has also noted that with decreasing resistivity contrast between a polarizable body and the host rock, the intensity of IP processes increases and the difference between the spectra of $\rho_a^*(\omega)$ and $\rho^*(\omega)$ decreases. However, in the case of a significant electrical conductivity contrast between a polarizable body and the host rock, the shape of the spectra of $\rho_a^*(\omega)$ can be significantly distorted. Liu and Vozoff (1985) have shown that the polarization intensity of polarizable bodies depends nonlinearly on the electrical conductivity from their host rock and the total contribution to $\rho_a^*(\omega)$ from bodies with different frequency characteristics can be considered as the superposition.

In the present paper, transient IP characteristics in piecewise homogeneous media are analyzed by mathematical modeling using various models. The effect of the contrast between geoelectric sections in resistivity, depth of polarizable bodies, and their structure is investigated. A comparison is made of the standard and spectral approaches to data analysis, and an estimate is given of the information content of the spectral IP parameters that have not previously been used for the analysis of field data.

Induced polarization in the time domain and the parameters used

The secondary electric fields formed in rocks due to external currents are studied in the time domain or the frequency domain, depending on the type of current source (AC or DC).

Time-domain IP is described using the notion of the transient characteristic (f(t)), which is understood as the rock response to a step change in current (Komarov, 1980). According to this definition, the voltage decay curve of the secondary electric field of IP after application of an infinitely long current pulse can be written as (Tarasov and Titov, 2007):

$$U_{\mathrm{IP}}(t) = M \cdot U_0 (1 - f(t)/U_0) = M \cdot U_0 \cdot F(t), \tag{1}$$

where t is the time counted from the time of switching-off of the current; $F(t)$ is the normalized transient characteristic of IP; $U_0 = \lim_{t \to \infty} U(t)$ is the asymptotic voltage corresponding to the infinitely long current pulse; M is the steady-state polarizability.

The total chargeability ore in expression (1) characterizes the intensity of IP processes:

$$M = \frac{U_0 - U_\infty}{U_0}, \tag{2}$$