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Negative apparent chargeability in time-domain induced polarisation data

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ABSTRACT

It appears to be relatively common to assume that negative apparent chargeability data in time-domain induced polarisation (IP) surveying is a sign of bad data quality. Negative IP data can however occur as a consequence of the distribution of chargeable zones in the ground, which is well documented in literature. A general mechanism behind negative IP data is proposed as follows; if the chargeable zones are mainly located in zones of negative sensitivity, and there is low or no chargeability in the positive sensitivity volumes in the investigated volume, it will result in negative apparent chargeability.

Numerical modelling confirms that the phenomenon will typically occur for longer electrode separation if the chargeability is concentrated in a thin layer at the surface only, but that other distributions of the chargeable bodies can also cause negative IP data. Different electrode arrays differ in tendency to produce negative IP data, where dipole–dipole and pole–dipole arrays are more prone to generate negative data than nested arrays in the modelled examples. In addition to the relative location of the chargeable zone the resistivity is important for its impact on the apparent chargeability.

Field data recorded in connection with the 3rd International IP Workshop on Ile d'Oléron in April 2014 confirm that negative apparent chargeability can be caused by a thin chargeable layer at the surface. The abundant negative IP data can be explained by an inverted model with low residuals, in which the chargeability is concentrated in a thin layer with modest chargeability close to the surface. Removing the data with negative apparent chargeability before inversion results in apparently poor resolution of the bottom layer and artefacts that are not present in the inversion results from the original data set. The results clearly demonstrate that negative apparent chargeability data can be a result of the distribution of chargeable zones in relation to the sensitivity distribution, and that such data should not be edited away on a routine basis since they contain important information.

1. Introduction

Earth resistivity tomography (ERT) has become widely used for engineering and environmental applications in the last couple of decades thanks to the relatively fast and simple field procedure in combination with availability of easy to use inversion software (Auken et al., 2006; Dahlin, 2001; Loke et al., 2014). Many modern ERT instruments can measure time-domain induced polarisation (TDIP), and it has been shown that IP can significantly enhance the information for environmental and engineering applications (e.g. Dahlin et al., 2010; Gazoty et al., 2012; Leroux et al., 2007). However, measurement of resistivity is very robust from a data quality point of view, whereas IP data acquisition is much more sensitive to noise contamination of the data due to smaller signal levels in combination with shorter delays and integration times (Dahlin and Leroux, 2012). This is particularly critical if the IP data is intended for extraction of spectral information, which is a way ahead for enhancing the information content that can be extracted from TDIP data (Fiandaca et al., 2012, 2013; Hönig and Tezkan, 2007).

In order to develop robust routines for data quality assessment of TDIP data it is essential to have a physically based understanding of possible IP responses. In DC resistivity surveying negative data are generally a sign of measurement technical problem unless the electrode layout geometry is such that the geometrical factor is negative, although there can be exceptions to this due to 3D geological structures (Jung et al., 2009). It appears to be a common belief that the same applies to induced polarisation (IP) measured in time domain, at least within the near surface geophysics community, and that negative IP data are a sign of data quality problems. It is thus not uncommon to edit away all negative IP data as part of a data processing routine, but this can lead to loss of important information as explained below.

It is well documented that negative IP data can occur as a result of a shallow chargeable zone or layer (Bertin, 1976; Loeb, 1976; Sumner, 1976), and it was understood that it could be caused by a simple

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geometric effect (Loeb, 1976). The mineral prospection IP community is probably aware of this, and Ranieri et al. (1996) have presented such results from a hydrogeological survey. Dieter et al. (1969) presented numerical modelling results for 1D soundings over spheres and ellipsoids that demonstrated that negative apparent chargeability can occur around such laterally limited bodies. Nabighian and Elliot (1976) studied 1D soundings over horizontally layered structures, and presented an analytical solution for the three layer case. They concluded that negative IP effects can be obtained whenever polarizable layers are overlying resistivity sequences of type K ($\rho_1 < \rho_2 > \rho_3$) and type Q ($\rho_1 > \rho_2 > \rho_3$).

We present a generally applicable way of explaining negative apparent chargeability caused by the geometric distribution of chargeable zones based on the sensitivity function, with the aim to provide an easier way to understand why and under which circumstances it can occur in complex geometries with 2D as well as 3D variation in the ground properties. Numerical modelling examples and a field example are used for demonstration. The forward and inverse modelling is limited to the integral chargeability, whereas modelling of full decay curves is left to future studies.

2. Sensitivity distribution and negative IP data

2.1. Resistivity sensitivity distribution

The sensitivity distribution determines how different parts of the ground contribute to the measured apparent resistivity of a particular four electrode array. The sensitivity distribution of vertical cross sections through the 3D sensitivity distribution for some common electrode arrays is shown in Fig. 1. The relative contribution of different parts of the ground is weighted with the magnitude of the sensitivity function, so that higher values of the sensitivity function gives a higher influence on the measured value. The sensitivity is given by the Fréchet derivative which can be calculated analytically for homogeneous ground (McGillivray and Oldenburg, 1990). The sensitivity distributions are different for inhomogeneous ground and have to be estimated by numerical modelling.

It can be noticed that the sensitivities are much higher at the surface close to the electrodes than at larger depths (Fig. 1). This means that near surface variation will have a major impact on the measured values, and that this must be accounted for carefully in the interpretation of the data in order to recover the more subtle contributions from deeper strata. Furthermore it can be noted that there are major zones of negative sensitivity, for example in between the C and P electrodes for the nested arrays (Fig. 1a–d) and between the C and P dipoles for the dipole–dipole array (Fig. 1e–f). The negative sensitivity leads to effects that can be counter intuitive, e.g. in otherwise homogeneous ground insertion of a high resistive block in a zone with negative sensitivity would lead to a smaller measured apparent resistivity.

2.2. Sensitivity distribution and IP effect

The sensitivity distribution will have consequences for the possible occurrence of negative apparent chargeability. To illustrate the mathematical relationship between the apparent IP values and the model resistivity sensitivity, we use the theoretical formulation by Seigel (1959). The apparent IP value (M_a) is given by a summation of the intrinsic IP (m) of all the regions of the subsurface.

$$M_a = \sum_{j=1}^{n} B_j m_j$$

where the model has n discrete regions. The coefficient B_j is given by

$$B_j = \frac{\rho_j}{\rho_a} \frac{\partial \rho_a}{\partial \rho_j}$$

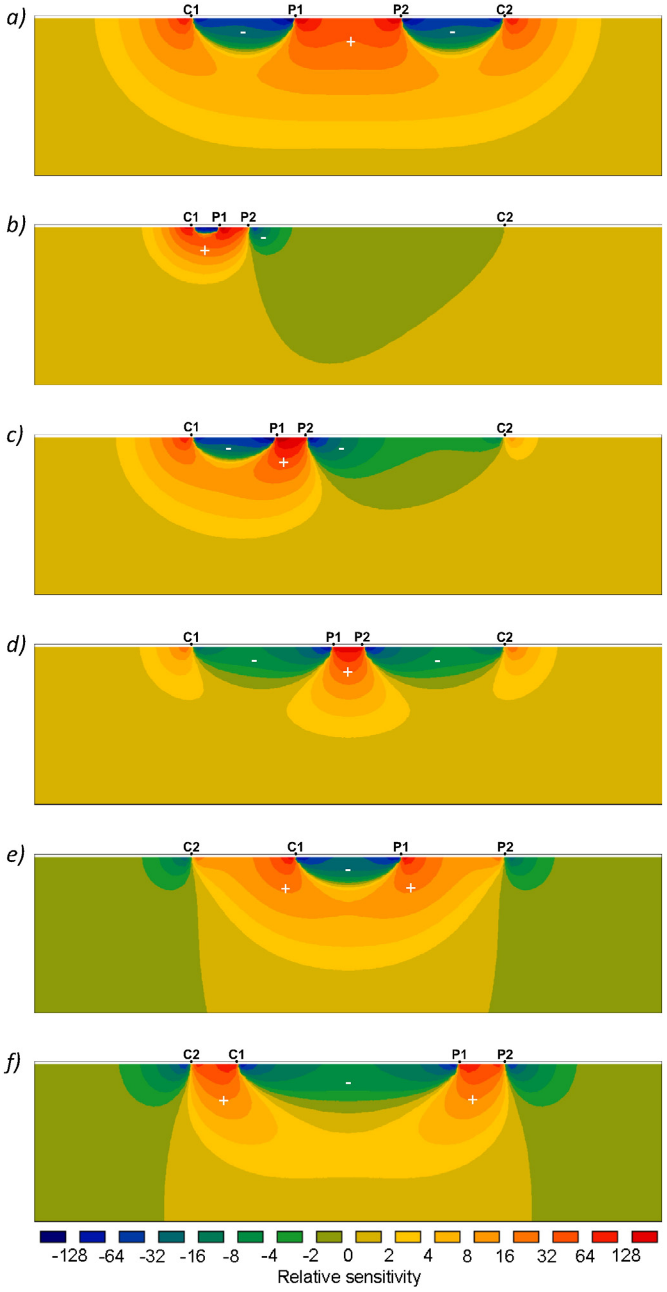

Fig. 1. Sensitivity distribution for; a) Wenner array, b) multiple gradient array (s = 9, n = 1), c) multiple gradient array (s = 9, n = 3), d) multiple gradient array (s = 9, n = 5), e) dipole–dipole array (n = 1), and f) dipole–dipole array (n = 5).

where ρ_a is the apparent resistivity and ρ_j is the model resistivity. In a region of the subsurface where the partial derivative term is negative, the contribution of that region to the apparent IP value is also negative. We note that the partial derivative $\frac{\partial \rho_a}{\partial \rho_j}$ is basically the integral of the Frechet derivative (sensitivity) over the volume of the jth region of the subsurface. The Frechet derivative is independent of the resistivity for a homogenous medium. However, it is dependent on the resistivity distribution for a non-homogenous medium. Nabighian and Elliot (1976) derived the equations for the B_j terms for a 1-D layered earth model. For general 2-D and 3-D models, the partial derivative values can be calculated numerically using the adjoint-equation method (McGillivray and Oldenburg, 1990).

Consider a chargeability distribution with a thin chargeable top layer overlying a layer with no detectable chargeability, as illustrated by the

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