

A REVIEW OF THE SELF-POTENTIAL METHOD APPLIED TO GROUNDWATER INVESTIGATION

V. Naudet, A. Binley
Department of Environmental Science,
Lancaster University, Lancaster LA1 4YQ, U.K.

Abstract

Standard geophysical methods detect the presence of water by changes of ground physical properties, but none of them are sensitive to groundwater fluxes except the self-potential (SP) method. This method consists of measuring the natural electric field within the subsurface with non-polarizable electrodes. These electrical potentials are mainly related to groundwater flow through the electrokinetic effect and organic matter-rich contaminant plumes through the "electro-redox" effect. This paper presents a short review of recent advances in the self-potential method for groundwater characterization. We present field and laboratory experiments that have improved our knowledge on the relationship between self-potential-signals and hydro-geochemical properties.

1 Introduction

The hydrological and geochemical characterization of groundwater typically involves drilling boreholes. These conventional invasive methods can be cost and time-consuming, and can potentially disturb the in-situ conditions of interest. Moreover, as these measurements are often sparse it is difficult to provide sufficient information about field-scale hydrogeologic heterogeneity. Geophysical methods are rapid, non-destructive, relatively inexpensive, and can vastly improve the characterization of the shallow subsurface. This explains an emerging interest in developing and using geophysical methods providing complementary hydrogeological and hydrogeochemical information to that obtained in piezometers. In this paper, we present a review of recent advances in theoretical and experimental aspects of the self-potential method, a powerful method that has proven recent advantages applied to hydrogeology problems.

The self-potential (SP) method involves the passive measurement of the electrical potential distribution at the ground surface of the Earth with non-polarizable electrodes. These electrodes, often called "porous pots", are designed so as not to create any spurious chemical potential upon contact with the ground. Self-potential field surveys are conducted by measuring electrical potential differences between pairs of electrodes that contact the surface of the Earth at a number of survey stations in the area of interest. These stations may be along profiles or spaced so as to obtain spatial coverage. One station is selected as a base station and all potentials are referenced to that point. The base station should be located at a point removed from expected anomalous activity. Measurements are made by connecting a high impedance voltmeter between at least two electrodes, usually the base station and a roving electrode. Data are plotted as profiles (observed potential versus distance along the profile) or, if the data provides sufficient coverage, as contour plots. The SP method has therefore the key advantage of being non-destructive, fast, inexpensive and very simple to implement in the field requiring only high impedance millivoltmeter (10^8 Ohms internal impedance) and at least two non-polarizable electrodes connected through a reel of wire.

SP anomalies are associated with charge polarisation mechanisms occurring at depth. The three main mechanisms are (1) the streaming potential due to electrokinetic coupling (Fournier, 1989; Birch, 1998), (2) the membrane or diffusion potentials due to chemical potentials gradients of ionic species (Maineult *et al.*, 2004), and (3) the "electro-redox" effect associated with redox potential gradients (Corry 1985; Naudet *et al.*, 2004, 2005). All these mechanisms are related to chemical potential gradients of charges carriers creating polarization in the porous media.

2 Background on SP electrokinetic sources

The electrokinetic effect corresponds to the generation of an electrical field associated to groundwater flow in a porous media. At the microscopic scale of the porous rock, the electrical field is due to the drag of the excess of charge contained in the vicinity of the pore water-mineral interface by the pore water flow. The key-parameter of this phenomenon is the electrokinetic coupling coefficient (C) related to the electrical field difference ($\nabla\varphi$) versus the hydraulic pressure difference ($\nabla\mathbf{p}$) (Revil *et al.* 1999). The equations associated to the fluid flow and the electrical current flow are related through this coupling coefficient. From a thermodynamic point of view, the existence of a measurable electrical field at the ground surface is related to the existence of a driving source current density in the ground, noted (\mathbf{J}_s). The total electrical current density (\mathbf{J}) in an isotropic porous material is the sum of the conduction current described by the Ohm's Law, and the driving source current density (\mathbf{J}_s) associated with the pore fluid pressure field.

$$\mathbf{J} = -\sigma\nabla\varphi + \mathbf{J}_s \quad (1)$$

In the case of the electrokinetic effect, the driving current source is associated with the pore fluid pressure field as:

$$\mathbf{J}_s = C\nabla\mathbf{p} \quad (2)$$

And C is the electrokinetic coupling coefficient:

$$C = -\frac{L}{\sigma} \quad (3)$$

In equations (1) to (3), φ and \mathbf{p} are the electrical potential (in V) and the fluid pressure (in Pa), respectively, σ is the electrical conductivity of the porous rock (in S m⁻¹), C is the electrokinetic coupling coefficient (expressed in V Pa⁻¹) and L is an electrokinetic coupling term (in A Pa⁻¹ m⁻¹). Using equation (1) and the continuity equation (conservation of charge), the electrical potential obeys to:

$$\nabla^2\varphi = \frac{1}{\sigma}\nabla\mathbf{J}_s - \frac{\nabla\sigma}{\sigma}\nabla\varphi \quad (4)$$

The distribution of the electrical potential is the sum of two terms. The first term is related to the current density (primary sources of polarization) and the second one is related to electrical resistivity heterogeneities in the porous system (secondary sources of polarization). For more details related to the theory of the electrokinetic effect see Revil (2002).

In the following section, we will present several field and laboratory experiments carried out to focus the link between geophysics and hydrology and geochemistry.

3 Field and laboratory Applications

3.1 Characterization of groundwater flow

Pumping test experiments with monitoring piezometers, represent the most common method to obtain information related to the flow and transport properties as hydraulic transmissivity of aquifers (e.g., Domenico and Schwartz, 1997). As stated earlier, the flow of groundwater is responsible for a measurable electrical field at the ground surface owing to the electrokinetic coupling between the Darcy velocity and the electrical current density. Therefore, it should be possible to invert the pattern of the electrical field measured at the ground surface during a

pumping test experiment to get out some information about the pattern of fluid flow and hydraulic parameters.

In the 1970's, Bogoslovsky and Ogilvy (1973) observed a significant positive self-potential anomaly (≈ 40 mV) around a pumping well in response to a pumping test experiment in steady-state conditions (Figure 1a). Revil *et al.* (2003) have proposed three methods to interpret these data: (1) a semi-empirical approach relating linearly the self-potential signal to the depth of the water (note that many authors, such as Jackson and Kauahikaua, (1987) and Aubert and Atangana (1996) have observed a similar relationship), (2) a tomographic algorithm based on a normalized cross-correlation algorithm, and (3) an inversion scheme using the Simplex algorithm. Their analysis is based on the conceptual model of Fournier (1989), which considered each element of the water table, in steady state conditions, as an elementary dipole with an inclination locally perpendicular to the water table and strength proportional to the water table elevation. The three methods proposed by Revil *et al.* (2003) determine the shape and range of possible depths of the water table from the study of the self-potential distribution recorded at the ground surface.

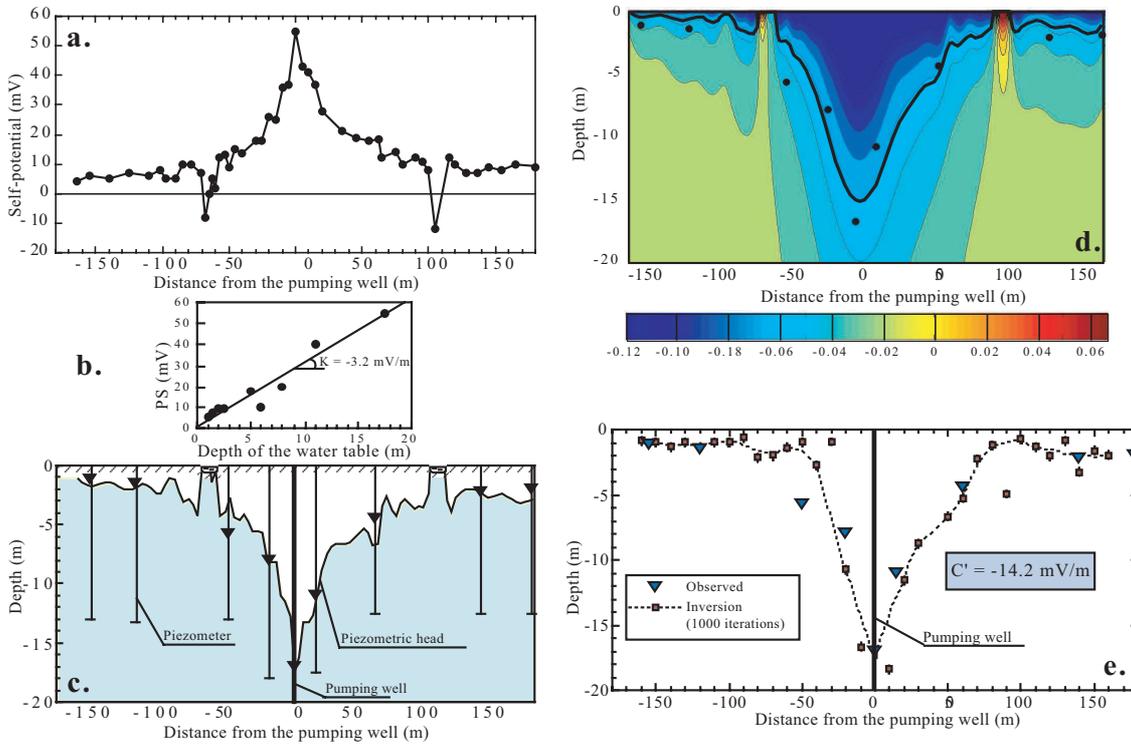


Figure 1: Self-potential signal (SP) associated to the pumping test (from Bogoslovsky and Ogilvy, 1973). b. Correlation between SP and the depth of the water table measured on monitoring wells (black lines with solid triangles). Determination of the piezometric level from: c. the semi-empirical method, d. the cross-correlation method, and e. the Simplex method. (Adapted from Revil *et al.*, 2003)

Figure 1 presents the results of the inversion of the self-potential data from Bogoslovsky and Ogilvy's (1973). From the semi-empirical approach, Revil *et al.* (2003) provide a surprisingly good estimation of the depth and shape of the water table (Figure 1c) with a coefficient $K = -3.2$ mV/m (Figure 1b). Application of the tomographic algorithm provides a set of possible water table shape (Figure 1d). The non-uniqueness of the solution is removed if one knows either the electrokinetic coupling coefficient or the water table at one location and under the assumption of the spatial homogeneity of the electrokinetic coupling coefficient. Using this in-

formation, the water table is determined everywhere and represented as a bold line in Figure 1b. Results from the Simplex algorithm are shown on Figure 1e. There is a relatively good agreement between the predictions of these three techniques and the water table delineated from the water level observed in the piezometers located around the pumping well (solid triangles).

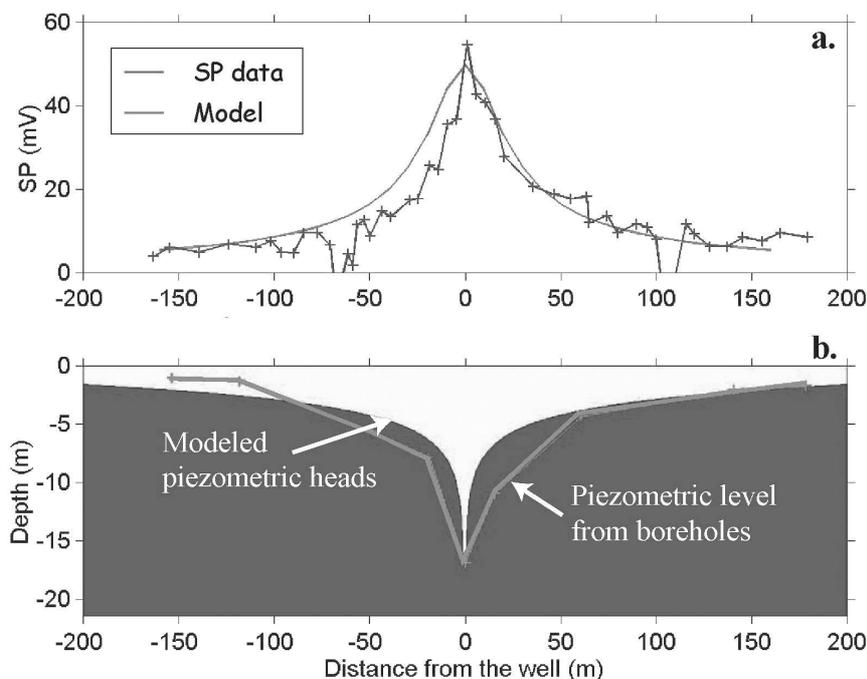


Figure 2: Result of the inversion by Darnet *et al.* (2003) of the Bogoslovsky and Ogilvy (1973) SP data. They found a bedrock depth $Z = 28m$, a ratio of the flow rate and the hydraulic conductivity $Q/K = 290 m^2$ and an electrokinetic coupling coefficient $C = -0.8 mV.m^{-1}$. (Adapted from Darnet *et al.*, 2003)

Darnet *et al.* (2003) also inverted these data with a genetic algorithm and have joint the self-potential theory with a hydraulic model to determine the depth and thickness of the aquifer and also the hydraulic conductivity (Figure 2). However, there is a lack of information regarding the field data described by Bogoslovsky and Ogilvy (1973) to test fully interpretation methods of these self-potential signals.

Recently, Rizzo *et al.* (2004) performed a pumping test experiment and monitored both piezometric levels and self-potential signals during the steady-state and relaxation phases. Using hydraulic models during these two phases of experiment, they joined the hydraulic and electric theories to analyze the self-potential data. With this joint equation, it has been possible to relate the time-lapse distribution of the self-potential signals to the distribution of hydraulic heads, and, then to hydraulic conductivity and storativity of the aquifer (Figure 3). The independently obtained estimation of the hydraulic conductivity and storativity based on the Theis scheme confirms electrically assessed values.

Using this well-constrained field work, Titov *et al.* (2005) made a numerical analysis of Rizzo *et al.*'s data with the numerical simulator GWFGEM (Ground Water Flow Geo-Electrical Mapping), which is based on a finite-difference method. From this modelling they reproduced the self-potential signals measured by Rizzo *et al.* (2004), taking into account the electrical resis-

tivity distribution mainly due to the metallic casing of the wells. The modelled self-potential values were consistent with the measured values.

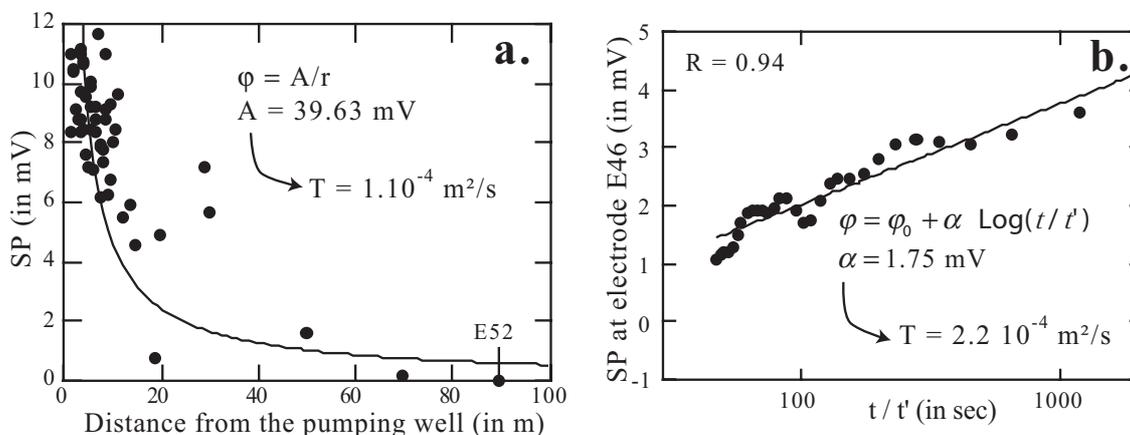


Figure 3: Determination of the transmissivity (T) of the aquifer from self-potential (SP) analysing during the steady-state condition (figure a) and the relaxation phase (figure b) of a pumping test experiments. (Adapted from Rizzo *et al.*, 2004)

Pumping tests have also been monitored with the self-potential method on laboratory experiments. Suski *et al.* (2004) measured the hydraulic and electric responses associated with a pumping test in a Plexiglas sandbox and the relaxation of these signals after the shutdown of the pump. In this controlled experiment, they obtained the same results as Rizzo *et al.* (2004) in the field providing evidence of a relationship between the electrical signals and the piezometric heads.

These field and laboratory results show that the record of the self-potential with a set of non-polarizable electrodes at the ground surface can be effectively used to reconstruct the shape of the water and determine the hydraulic parameters of the aquifer during controlled pumping tests.

3.2 Characterization of groundwater quality

For the purpose of risk assessment of contaminated sites and the use of remediation methods, it is very important to know how and where the anaerobic contamination can spread or decline over time. In this situation, the self-potential method appears as an economical and fast reconnaissance tool to monitor redox conditions and to delineate the shape of the contamination plume. In the case of contaminated groundwater, the main self-potential sources are associated with (1) groundwater flow (electrokinetic effect), (2) concentration gradients (diffusion or membrane potential) and (3) redox potential gradients (electro-redox effect).

Naudet *et al.* (2003, 2004) have shown that it is possible to determine the redox potential values of a contaminated aquifer from self-potential measurements. They have performed intense self-potential measurements on the Entressen landfill site (Provence, Southern France). This landfill, which has been active since 1912, is responsible for an organic-rich contaminant plume spreading in a shallow unconfined aquifer. After removing the electrokinetic component associated with the groundwater flow, then, a strong negative anomaly (several hundreds of millivolts) was observed to be correlated with the contaminant plume. Moreover, as a first approximation, the strength of residual self-potential signals has been shown to be directly proportional to the

redox potential (Naudet *et al.*, 2004) (Figure 4.a).

To further evaluate the potential role of bacteria in the generation of an electrical current, Naudet and Revil (2005) performed sandbox experiments in which self-potential signals and redox potential variations were monitored in presence of sulfate-reducing bacteria. A linear relationship was also observed apparently related to bacteria activity (Figure 4.b). From these considerations, these authors proposed a (bio)-geobattery concept in which biofilms and/or biominerals (precipitation of metallic particles induced by biomineralization) at the redox front allow electron transfer (therefore a net driving current density) between the reduced and oxidized parts of the system. In turn, this current is responsible for an electrical field measurable at the ground surface as self-potential anomalies.

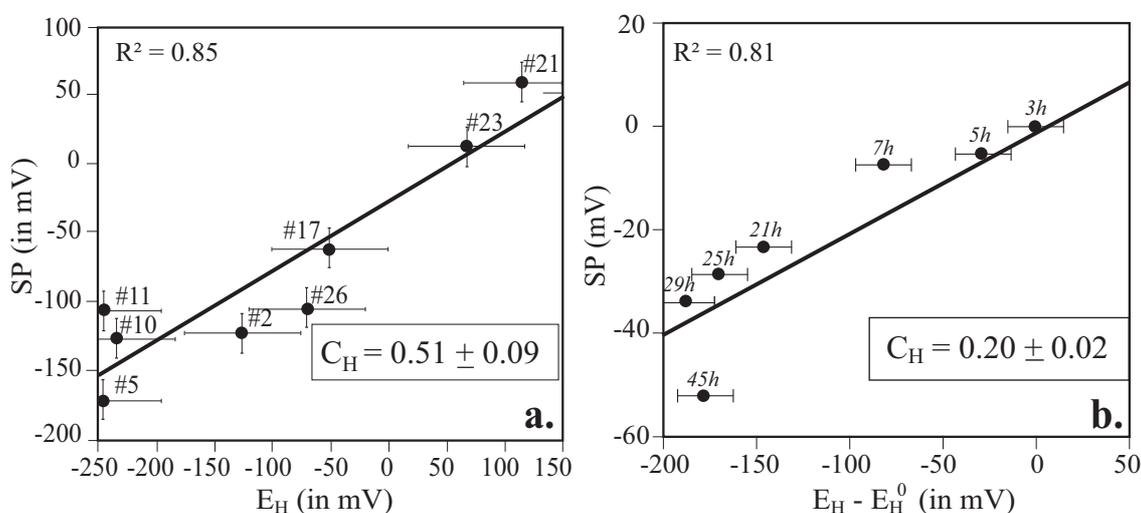


Figure 4: Correlation between self-potential (SP) data and redox potential (EH) data from the Entressen field study (Naudet *et al.* 2004) (Figure a) and from the sandbox experiments (Naudet and Revil, 2005) (Figure b.).

From a series of laboratories experiments in a sandbox, Mainault *et al.* (2004) have shown the possibility to detect advective transport of NaCl and KCl and ionic diffusion of NaCl in stagnant fluid from self-potential monitoring. They observed significant electric potential differences associated to the arrival of the salt front. Therefore, monitoring these electrical potential differences can be useful to determine the motion of the concentration front.

These field and laboratory experiments show that the self-potential methods can provide a means for the detection and quantification of contaminants in groundwater prior to remediation when used with a minimum of in-situ measurements.

4 Conclusions

The self-potential method offers a simple non-intrusive mean to characterize passively groundwater flows. As the electrical sensors (electrodes) are cheap, the self-potential method can be used in the field to provide a dense resolution of electrical signals related to the studied phenomena (dynamic or chemical state of the groundwater). Then, such a high-resolution map combined with a minimum of hydrogeological and/or geochemical data can provide spatial distributions of groundwater parameters (hydraulic heads, redox potential, ionic concentrations, etc).

Further controlled field and laboratory studies of the self-potential method are required to fully understand the influence of (1) microbiological states of contaminant plumes, (2) fluid transfer in the vadose zone, and (3) electrical resistivity contrasts in the subsoil. Based on these experiments and resulting models, robust inversion scheme could be developed to better interpret self-potential data as hydraulic and geochemical parameters. We expect that this method will find a great interest among the hydrogeological community in the near future.

References

- [1] Aubert, M., and Q. Y. Atangana, Self-potential method in hydrogeological exploration of volcanic areas, *Ground Water*, 34, 1010- 1016, 1996.
- [2] Birch F S., Imaging the water table by filtering self-potential profiles, *Ground Water*, 36(5), 779–782, 1998.
- [3] Bogoslovsky V. V. and A A. Ogilvy, Deformations of natural electric fields near drainage structures, *Geophysical Prospecting*, 21, 716–723, 1973.
- [4] Corry, E., Spontaneous polarization associated with porphyry sulphide mineralization, *Geophysics*, 50, 1020-1034, 1985.
- [5] Darnet, M., G. Marquis, and P. Sailhac, Estimating aquifer hydraulic properties from the inversion of surface Streaming Potential (SP) anomalies, *Geophys. Res. Lett.*, 30(13), 1679, doi:10.1029/2003GL017631, 2003.
- [6] Domenico, P. A., and F. W. Schwartz, *Physical and Chemical Hydrogeology*, 2nd ed., John Wiley, Hoboken, N. J, 1997.
- [7] Fournier, C., Spontaneous potentials and resistivity surveys applied to hydrogeology in a volcanic area: Case history of the Chaîne des Puys (Puy-de-Dôme, France), *Geophys. Prospect.*, 37, 647- 668, 1989.
- [8] Jackson, D. B., and J. Kauahikaua, Regional self-potential anomalies at Kilauea Volcano, *U.S. Geol. Surv. Prof. Pap.*, 1350, 947–959, 1987.
- [9] Maineult A., Y. Bernabé and P. Ackerer, Electrical response of flow, diffusion and advection in a laboratory sand box, *Vadoze Zone Journal*, 3, 1180–1192, 2004.
- [10] Naudet V., A. Revil, J-Y. Bottero and P. Bégassat, Relationship between self-potential (SP) signals and redox conditions in contaminated groundwater, *Geophysical Research Letters*, 30, 2091, doi:10.1029/2003GL018096, 2003.
- [11] Naudet V., A. Revil, J-Y. Bottero and P. Bégassat, Relationship between self-potential (SP) signals and redox conditions in contaminated groundwater, *Geophysical Research Letters*, 30, 2091, doi :10.1029/2003GL018096, 2003.
- [12] Naudet V., A. Revil, E. Rizzo, J.-Y. Bottero and P. Bégassat, Groundwater redox conditions and conductivity in a contaminant plume from geoelectrical investigations, *Hydrology and Earth System Sciences*, 8, 1, 8–22, 2004.
- [13] Naudet V., and A. Revil, A sandbox experiment to investigate bacteria-mediated redox processes on self-potential signals, *Geophysical Research Letters*, 32(11), L11405, doi:10.1029/2005GL022735, 2005.
- [14] Revil A., P. A. Pezard and P. W. J. Glover, Streaming potential in porous media. 1. Theory of the zeta potential, *Journal of Geophysical Research*, 104, 20021–20031, 1999.
- [15] Revil A., The hydroelectric problem of porous rocks: thermodynamic approach and introduction of a percolation threshold, *Geophysical Journal International*, 151 ,944–949, 2002.
- [16] Revil A., V. Naudet, J. Nouzaret, and M. Pessel, Principles of electrography applied to self-potential electrokinetic sources and hydrogeological applications, *Water Resour. Res.*, 39, 5, 1114, doi:10.1029/2001WR000916, 2003.

- [17] Rizzo E., B. Suski, A. Revil, S. Straface and S. Troisi, Self-potential signals associated with pumping-tests experiments, *Journal of Geophysical Research*, doi:2004JB003049, 2004.
- [18] Suski B., E. Rizzo, and A. Revil, 2004, A sandbo experiment of self-potential signals associated with a pumping test, *Vadose Zone Journal*, 3, 1193-1199.
- [19] Titov K., A. Revil, P. Konosavsky, S. Straface and S. Troisi, 2005, Numerical modelling of self-potential signals associated with a pumping test experiment, *Geophys. J. Int.*, 162, 641-650 doi:10.1111/j.1365-246X.2005.02676.x