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Passive electrical monitoring and localization of fluid leakages from wells

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S U M M A R Y

Electrokinetic phenomena are a class of cross-coupling phenomena involving the relative displacement between the pore water (together with the electrical diffuse layer) with respect to the solid phase of a porous material. We demonstrate that electrical fields of electrokinetic nature can be associated with fluid leakages from wells. These leakages can be remotely monitored and the resulting signals used to localize their causative source distribution both in the laboratory and in field conditions. The first laboratory experiment (Experiment #1) shows how these electrical fields can be recorded at the surface of a cement block during the leakage of a brine from a well. The measurements were performed with a research-grade medical electroencephalograph and were inverted using a genetic algorithm to localize the causative source of electrical current and therefore, localize the leak in the block. Two snapshots of electrical signals were used to show how the leak evolved over time. The second experiment (Experiment #2) was performed to see if we could localize a pulse water injection from a shallow well in field conditions in the case of a heterogeneous subsurface. We used the same equipment as in Experiment #1 and processed the data with a trend removal algorithm, picking the amplitude from 24 receiver channels just after the water injection. The amplitude of the electric signals changed from the background level indicating that a volume of water was indeed flowing inside the well into the surrounding soil and then along the well. We used a least-square inversion algorithm to invert a snapshot of the electrical potential data at the injection time to localize the source of the self-potential signals. The inversion results show positive potential anomalies in the vicinity of the well. For both experiments, forward numerical simulations of the problem using a finite element package were performed in order to assess the underlying physics of the causative source of the observed electrical potential anomalies and how they are related to the flow of the water phase.

1. Introduction

Various types of fluid leakages that may potentially occur near a wellbore are shown in Fig. 1. This involves flow through the steel casing of a well, through the cement, or along the casing/cement interface, the cement/formation interface, or within a set of micro-fractures in the cement sheath. Our goal is to develop methods to diagnose such fluid leakage occurrences and to localize them over time. Some of these leakages can be associated with brittle deformation and with the generation of acoustic or seismic emissions, which can be measured remotely and inverted to localize the seismic source (position and moment tensor). While this is said, some leakages may be completely aseismic. Therefore, other methods are required to detect and localize these aseismic events.

The flow of pore water after a hydraulic fracturing operation and associated fluid leakages near the wellbore area results in measurable voltages both during field operations in reservoir environments (Entov et al., 2010; Chen et al., 2011), in shallow aquifers (Wishart et al., 2008), or associated with artificial seismic sources (Kuznetsov et al., 2001). Similar conclusions have been reached in volcanic environments where fluctuations of the electrical field can be observed at the surface of the Earth associated with natural

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fracturing processes (e.g., Byrdina et al., 2003). In porous media, the current density generating these self-potential anomalies is associated with the occurrence of the flow of the formation water in saturated or unsaturated conditions. The coupling is electrokinetic in nature, that is associated with the advective transport of the excess (or deficiency) of electrical charges in the pore water. This excess or deficiency of electrical charges is there to compensate for the deficiency or excess of electrical charges on the mineral surface.

There is also a growing literature base related to laboratory observations of electromagnetic fields associated with hydromechanical disturbances (Moore and Glaser, 2007; Wang et al., 2011; Haas et al., 2013; Revil and Jardani, 2013). A complete theory of these electrokinetic effects (that is associated with the relative displacement between the formation water and the rock matrix) has been developed by Mahardika et al. (2012) and Revil and Mahardika (2013). Alternatively, the same types of coupled methodology between hydromechanical and electrical disturbances can be used to identify the presence of microcracks in porous media using a spectral approach (Jougnot et al., 2013), to identify tidal effects in the deformation of glaciers (Kulessa et al., 2003), to perform hydraulic conductivity tomography using a joint inversion of self-potential and head data (Soueid Ahmed et al., 2014), or to infer large scale ground water flow in volcanic edifices (Byrdina et al., 2013).

Beside passive seismic, we are not aware of any other method able to remotely monitor instantaneously fluid leakages in the vicinity of a well. Recently, electrographic methods have been developed as a way to localize hydromechanical events from their electromagnetic signatures (Crespy et al., 2008; Mahardika et al., 2012; Revil and Mahardika, 2013; Haas et al., 2013). This idea is very similar to what is performed in electroencephalography to localize the causative current source of the electrical field fluctuations recorded on the scalp of a human patient or an animal. In biological situations, these currents are associated with the opening of ionic channels at the synapses between the neurons. A variety of deterministic and stochastic techniques have been developed in electroencephalography and in magnetoencephalography to address the inversion or localization problems. The approaches we will follow in this paper are not fundamentally distinct to what has been proposed in medical science (see Grech et al., 2008 for a review of these methods).

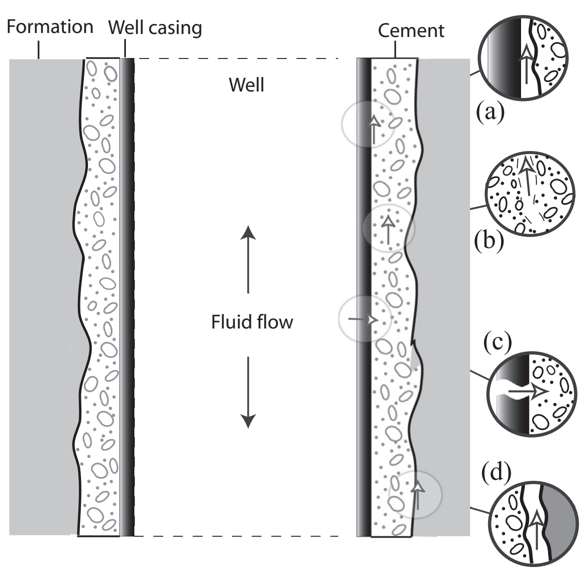

Fig. 1. Sketch showing the different possibilities for leakage from a well. Case (a) corresponds to the existence of cracks in between the steel casing and the cement sheath. Case (b) corresponds to the existence of microcracks in the cement. Case (c) corresponds to the existence of pathways directly in the steel casing of the well. Finally case (d) corresponds to the formation of microfractures between the cement and the geological formations. Adapted from Alberta Energies Utility Board, see http://www.psehealthyenergy.org/data/PSE__CementFailureCausesRateAnalaysis_Oct_2012_Ingraffea.pdf.

In this paper, we present and model two controlled experiments. The first experiment (Experiment #1) is performed in the laboratory and is a follow-up of the experiment described in Haas et al. (2013). Our goal is to analyze the position of two electrical bursts and to show how the localization of the causative source moves over time in the vicinity of the well. The second experiment (Experiment #2) corresponds to a small scale field experiment in which a water pulse was injected at a shallow depth of 65 cm. Electrical potential fluctuations are monitored at surfaces of the cement block in Experiment #1 or at the ground surface in Experiment #2 using a very sensitive voltmeter developed for electroencephalography. Our goal is to show that these electrical (self-) potential signals can be used to localize the pulse injection of water using stochastic or deterministic localization techniques. We call this localization approach "electrography". In addition, we perform numerical modeling using a finite element package in order to explain the laboratory data in terms of a water flow model and to demonstrate the consistency between the streaming potential hypothesis and the observations.

2. Physical concepts

In order to understand the type of electrical field anomalies associated with the leakage from a well (see Fig. 1), we need first to provide a description of the most probable type of mechanisms that can generate such anomalies. We will demonstrate below in Sections 3.5 and 4 that our observations are in agreement with an electrokinetic mechanism, which involves the relative displacement between the charged grains of a poorus material and the pore water. Electrokinetic coupling mechanisms between the hydromechanical equations and the electromagnetic equations are described in Mahardika et al. (2012) and Revil and Mahardika (2013) including dynamic terms related to inertial effects in the continuity and constitutive equations (Newton's and Darcy's laws). The governing equation for the occurrence of self-potential signals is obtained by combining a constitutive equation with a continuity equation. The constitutive equation corresponds to a generalized Ohm's law for the total current density $\mathbf{j}$ (A m^{-2}) (e.g., Sill, 1983),

$$\mathbf{j} = \sigma\mathbf{E} + \mathbf{j}_S, \tag{1}$$

where σ denotes the low-frequency electrical conductivity of the porous material (in S m^{-1}), $\mathbf{E} = -\nabla\varphi$ (φ denotes the electrical potential expressed in V) the electrical field in the quasi-static limit of the Maxwell equations for which $\nabla \times \mathbf{E} = 0$ ($\mathbf{E}$ in V m^{-1}) and electromagnetic induction is therefore neglected. The first term on the right side of Eq. 1 represents the conduction current density, and the second term represents the kinetically driven source current density (streaming current density). The source current density is given by $\mathbf{j}_S = \hat{Q}_V\mathbf{u}$ where $\mathbf{u}$ denotes the Darcy velocity and $\hat{Q}_V$ the excess of charge (of the diffuse layer) per unit pore volume of the porous or fractured material (in C m^{-3}) that can be dragged by the flow of the formation water. More precisely $\mathbf{u}$ (in m s^{-1}) denotes the flux of the water phase with respect to a Lagrangian framework associated with the deformation of the skeleton of the porous material. At high flow rates, the flow can be influenced by the value of the Reynolds number for the pervasive flow through the porous material; the case of high Reynolds numbers (>1 but smaller than 200) has been analyzed by Bolève et al. (2007).