Seismoelectric imaging with virtual electrode scanning

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Summary

Seismoelectric scans can be used for direct mapping of the electrical and hydraulic properties of oil and gas reservoirs or acquifers. The scans involve virtual seismic electrodes which are produced by focusing acoustic energy at known positions in the subsurface and at known times. If the acoustic focus point coincides with a discontinuity in electrical and hydrological medium properties, then it generates an electric current density which leads to a difference of potential that can be observed with remote electrodes. Although seismoelectric phenomena are not new, subsurface monitoring using virtual seismic electrodes provide a huge improvement over existing methodology for two main reasons: the source of the seismoelectric conversion is localized in space, and the energy at the conversion point is maximum. The seismoelectric source behaves like a controlled electrode whose properties depend on the acoustic energy pumped into the ground and on the local medium properties. By changing the position of the focus point through appropiate time delays of the acoustic sources, we can scan the medium properties and produce a map of its properties. This map can either be used directly, or it can aid electrical tomography by increasing its resolution and robustness.

Introduction

In non-destructive imaging, we use remote measurements of different physical quantities at the exterior of an object in order to infer internal physical properties and their spatial distribution. The main goal is to use these measurements to characterize the distribution of rocks and fluids in the interior of the earth. In this paper, we focus on the use of electric disturbances observed at the exterior of the earth and caused by the passage of an elastic wave through a heterogeneous medium composed of solid rock grains with pore spaces filled with different fluids (e.g., gas, oil, and water). The coupling between a seismic field and an electromagnetic disturbance is known as the seismoelectric effect, which has a long history in geophysics. The elastic wave causes movement of the fluids relative to the surrounding solid frame, which creates an electrical current due of the excess of electric charge contained in the pore water needed to balance the negative charge on the mineral surface. This current creates electromagnetic disturbances, which can be observed at a distance.

The seismoelectric effect is sensitive to the presence of fluids in rock pores, thus providing an opportunity to characterize fluid saturation, rock permeability, and other phenomena that cannot be observed just with elastic waves. Two main difficulties complicate the use of the seismoelectric effect in geophysical exploration and characterization. First, the seismoelectric effect is small, which limits its expression at a distance from the occurrence of an electric signal. In general, it is estimated that the electric field disturbances can be observed up to a kilometer from the position of such a conversion. Second, seismoelectric conversions occur at any location where an elastic wave is present at places where the medium solids and fluids are in direct contact. This limits our ability to associate an observed change in electric potential with a specific location in the subsurface.

Ideally, we would like to observe the seismoelectric effect associated with a <u>strong</u> elastic wave <u>localized</u> at a single point in space, at a given time. This would allow us to observe the strongest possible electric signal from a known location, assuming that the material properties at that location facilitate seismoelectric conversions, and would also reduce the ambiguity caused by conversions occurring simultaneously at many points in the medium. Our solution to this problem is to use multiple elastic sources synchronized in space and time in order to focus energy at a single target point. Focusing not only reduces the ambiguity of the seismoelectric conversion origin, but also insures that the elastic wave causing the conversion is maximized since all energy induced into the medium is concentrated at only one point, instead of being distributed throughout the medium. Elastic wavefield focusing at a given point produces a localized electric source, i.e. a virtual electrode (Sava & Revil, 2012), which can be used in monitoring the subsurface.

Focusing can be achieved in two main ways. First, we can use many sources at elastic energy activated at different locations in space at the same time. Waveforms injected into the medium with appropriate delays depending on the source position concentrate at the desired focus point and potentially trigger strong seismoelectric conversions. The drawbacks of this approach is that multiple elastic sources need to be available in the field at a given time, which is costly, and that the sources need to be precisely synchronized, which is technically difficult. Second, we can use a single source of elastic energy in the field, but activate it multiple times at different positions in space. Then, we can recombine the observed electric responses numerically based on timing that would be needed for the elastic energy to focus at a given location in the medium. The drawbacks of this approach is that the duration of the experiment is longer, since the elastic source is activated multiple times at different locations, and that the observed electric field for each individual source might be hampered by coherent or incoherent noise in the field.

We assume in our technique that the elastic properties of the medium are known with sufficient accuracy, for example, from wavefield tomography, such that the elastic waves can be reliably focused at a known location and at a known time. The strength of the observed seismoelectric potential depends on the acoustic field, but also on the (unknown) petrophysical properties at the source including the (unknown) electric properties in the medium. Identifying these properties is our main goal, and this can be accomplished through conventional seismoelectric inversion. That said, here we do not discuss about electrical resistivity tomography, but we focus on the forward problem and discuss how controlled virtual electrodes can aid seismoelectric inversion. We also assume, for simplicity, that we operate in the quasi-static regime of the Maxwell equations (Hu *et al.,* 2007; Jardani *et al.,* 2010; Araji *et al*. 2012).

Theory

The seismoelectric problem is formulated in terms of a coupling between the Maxwell equations and the Biot theory (e.g., Pride, 1994; Revil and Jardani, 2010). Here we present a simpler seismoelectric theory that is compatible with the acoustic approximation.

The acoustic approximation solves for the pressure within a porous material, *P,* containing a fluid that cannot support shearing (e.g. water)

$$\frac{\partial^2 P}{\partial t^2} - K\nabla\cdot\left(\frac{1}{\rho}\nabla P\right) = f(\mathbf{x},t) \quad \textbf{(1)}$$

Here, P denotes the confining pressure, ρ the mass density of the material, K the bulk modulus, and $f(\mathbf{x},t)$ the source function at position **x** and time t. In practice, we need to describe the pressure change on the material due to a pore fluid pressure change. In the undrained regime of poroelasticity the pressure P is related to the so-called undrained pore fluid pressure p by $p=BP$, where B is called the Skempton coefficient and depends on the rock bulk modulus, the undrained bulk modulus, and the bulk modulus of the solid phase. The passage of the wave generates a confining pressure fluctuation,, which leads to a change in the pore fluid pressure and therefore to the flow of the pore water according to Darcy's law relative to the solid phase, thus generating a source current density

$$\mathbf{j}_S = -\frac{\hat{Q}_V^0 k_0}{\eta_f}\nabla p \,. \quad \textbf{(4)}$$

The total current density **j** is the sum of a conduction current density plus the source current density associated with the flow of the pore water $\mathbf{j}_S$ (Pride 1994; Jardani *et al*. 2007)

$$\mathbf{j} = \sigma\mathbf{E} + \mathbf{j}_S \,, \quad \textbf{(5)}$$

where $E = -\nabla\psi$ is the quasi-static electrical field, and σ is the electrical conductivity of the porous rock. The volumetric source current density, caused by the passage of a wave through a heterogeneous material, is responsible for the radiation of electromagnetic energy. Under the quasi-static limit of the Maxwell equations, the electrical potential ψ is governed by the Poisson equation:

$$\nabla\cdot\left(\sigma\nabla\psi\right) = \nabla\cdot\mathbf{j}_S \quad \textbf{(6)}$$

This PDE allows us to evaluate the electric potential ψ given by an electroacoustic source current $\mathbf{j}_S$, which depends on the gradient of the acoustic field, as seen from Eq. 4.

Example

We consider a bimodal heterogeneous material, as shown in Figure 1. We also consider two wells in which seismic sources are located. This array is used because it offers the possibility to focus efficiently seismic energy anywhere between the wells. Our ability to focus energy at a point is directly related to the angular aperture of the array. As indicated earlier, in practice only one seismic source is needed, given the fact that the problem is linear. The focusing of the seismic energy can be done virtually by combining data collected at the receivers with the source placed at different locations. This construction is identical with techniques widely used in exploration seismology, e.g. plane-wave imaging, or in satellite monitoring, e.g. synthetic aperture radar.

We loop over many points in the medium and simulate seismic waves with a known source. The waves are recorded at the receivers distributed in the boreholes. The recorded signals are time reversed and re-injected in the medium. After back-propagation, the waves focus at the location of the original source and at the original time at which the source was triggered. At this time, seismoelectric conversions occur proportionally with the gradient of physical and hydraulic properties at the focus location. The associated electrical signal is recorded at the electrodes in the boreholes.

Focusing is done in order to scan each point of the material between the two wells. Figure 1 shows an example of wave propagation from a source located between the two wells. The backpropagated waves are similar, although some distortion may occur due to the limited aperture of the monitoring array. However, most of the energy injected into the medium returns to the original source position leading to a strong acoustic pulse at a known position and time.

Electrodes located in the wells record the electrical potential over time. The closest electrode captures the strongest signal from the seismoelectric conversion, but signals are captured all around the medium under investigation. The self-potential time series are measured with respect to a fictitious electrode located at infinity. The recorded potential at a given electrode is reported at the point where focusing occurs. The result is a map of electrical potential observed at a given electrode for all focus points located in the scan area, Figure 2.

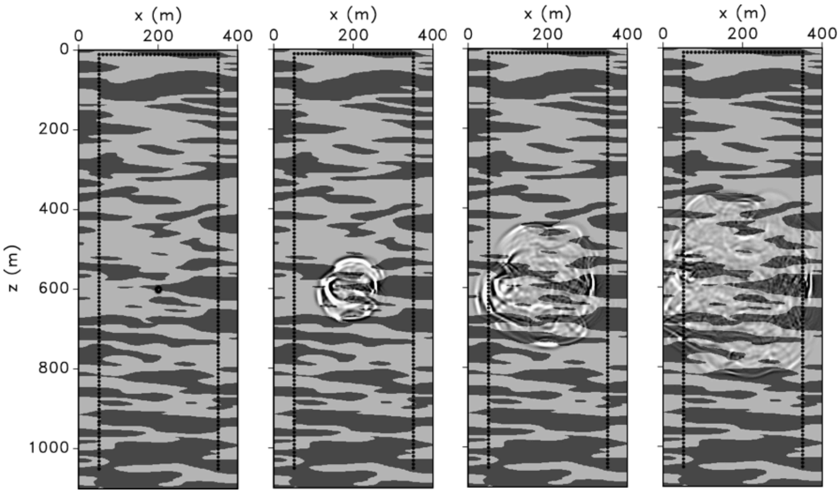

__Figure 1:__ Seismic wavefield associated with a source in the medium. Each frame corresponds to a different time step. The wavefield is recorded at boreholes surrounding the source point and can be used to reconstruct the wavefield using time-reversal.

Conclusions

We demonstrate the use of virtual seismic electrodes to the problem of mapping hydro-electric properties in the subsurface. The key to this method is to focus acoustic waves at specific coordinates from multiple or repeated acoustic receivers located in the vicinity of the target. The acoustic energy maximizes at the focus time, thus insuring the strongest possible seismoelectric source at the target position as well as localized seismoelectric conversions. The main applications of this methodology are in electric and hydraulic investigation of medium properties. This can be accomplished by surrounding the area of investigation with multiple electrodes at known positions where to observe seismoelectric energy. This methodology can also be employed to infer hydraulic parameters, for example, permeability, through a controlled seismoelectric procedure.

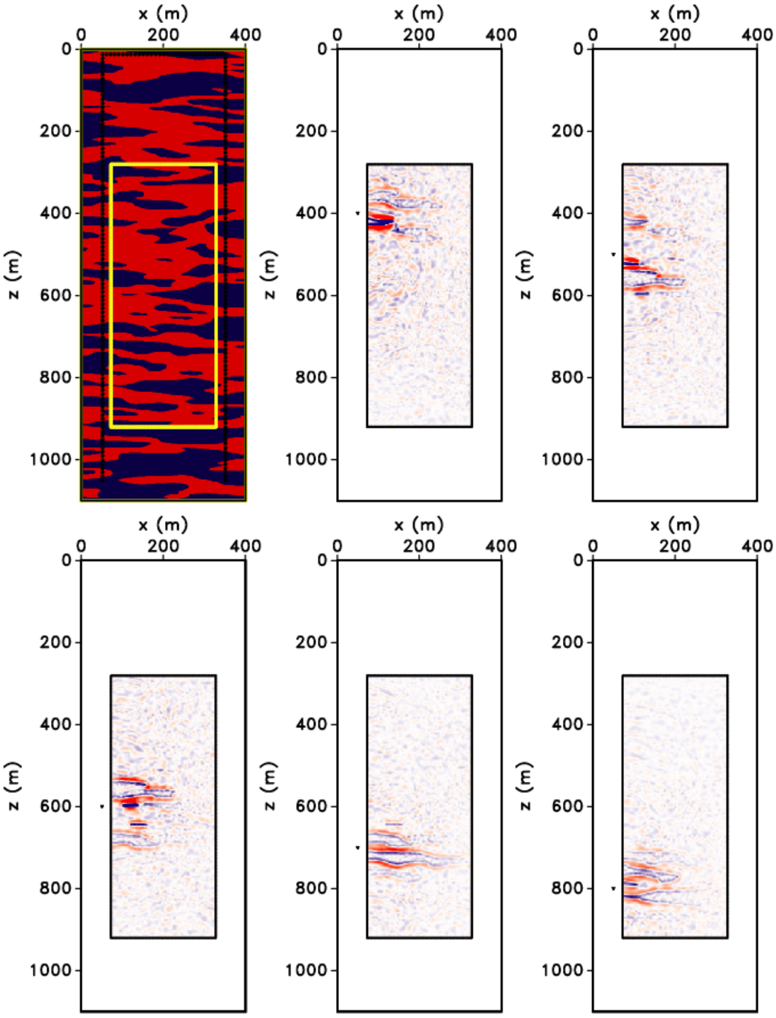

Figure 2: Distribution of the electrical potential recorded at various electrodes indicated in the images by red points. The electrical potential map illuminates the heterogeneities in the vicinity of the electrode (the reference electrode is supposed to be at infinity).

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