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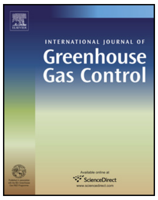

Borehole seismoelectric logging using a shear-wave source: Possible application to CO_2 disposal?

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ABSTRACT

The behaviour of CO_2 deposition sites – and their surroundings – during and after carbon dioxide injection has been matter of study for several years, and several geophysical prospection techniques like surface and crosshole seismics, geoelectrics, controlled source electromagnetics among others, have been applied to characterize the behaviour of the gas in the reservoirs. Until now, Seismolectromagnetic wave conversions occurring in poroelastic media via electrokinetic coupling have not been tested for this purpose. In this work, by means of numerical experiments using Pride's equations – extended to deal with partial saturations – we show that the seismoelectric and seismomagnetic interface responses (IR) generated at boundaries of a layer containing carbon dioxide are sensitive to its CO_2 content. Further, modeling shear wave sources in surface to borehole seismoelectric layouts and employing two different models for the saturation dependence of the electrokinetic coefficient, we observe that the IR are sensitive to CO_2 saturations ranging between 10% and 90%, and that the CO_2 saturation at which the IR maxima are reached depends on the aforementioned models. Moreover, the IR are still sensitive to different CO_2 saturations for a sealed CO_2 reservoir covered by a clay layer. These results, which should be complemented by the analysis of the IR absolute amplitude, could lead, once confirmed on the field, to a new monitoring tool complementing existing ones.

1. Introduction

Injection of large amounts of man-produced CO_2 in depleted oil wells below the sea floor and in other apropriate geological formations has been used, for several years, as a means of reducing the carbon dioxide emissisons into the atmosphere. For example, CO_2 is being injected in the Sleipner field in the North Sea since 1996 at a rate of 0.85 Mt per year (Ellis, 2010), and also beneath the Sahara desert, at In Salah in Algeria (Ringrose et al., 2009). The former has been a subject of extensive theoretical and experimental studies, including laboratory rock sample analysis, seismic monitoring, etc. We mention, from the large literature concerning this deposition site, the studies of Chadwick et al. (2009, 2010) where time-lapse seismic is employed to characterize CO_2 plume development, and the studies of Gomez and Ravazzoli (2011), where CO_2 content related to seismic attributes were investigated. Moreover, a test site in Ketzin, Germany, is being run and extensively studied in order to monitor the CO_2 behaviour during and after injection, see Martens et al. (2012, 2013) and references therein. Scientists from different areas have been studying this topic, and a still open problem is to predict the behaviour of the gas once set into the reservoir. Will it remain stable? Will it migrate, and make its way back to the surface? How the stored CO_2 can be efficiently monitored in order to avoid pollution of overlying aquifers by leaked gas, among other issues (Thibeau and Mucha, 2011) is still a topic of intense research.

Among other works implemented at Ketzin, Wiese et al. (2010) studied the hydraulic properties of the storage reservoir, Kazemeini et al. (2010) carried out some rock physics and seismic modeling studies of surface seismic CO_2 monitoring, and cross-well seismic tomography has been also performed (Zhang et al., 2012); more recently Fischer et al. (2013) made laboratory studies of geochemichal changes induced in Ketzin rock matrix samples by the presence of the stored carbon dioxide, and Wiese et al. (2013) studied – at the same site – not only the geochemical but also the hydraulic changes induced in the overburden by deposited CO_2. We can also mention that both seismic and electric methods are potentially appropriate to study the CO_2 reservoir (Fabriol

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et al., 2011; Girard et al., 2011; Carcione et al., 2012). Martens et al. (2012) describe not only the results of different campaigns including seismic, surface and borehole monitoring, but also some seismic simulation runs in order to check previous models; on the other hand synthetic and field geoelectrical methods were applied to study possible gas migration (Kiessling et al., 2010). Moreover Ishido et al. (2013) have numerically investigated the application of self potential methods to monitor the migration of CO_2 sequestrated into saline aquifers, concluding that the used methods are effective for sensing the approach of CO_2 to the well casings deep within the subsurface. We finally point out that in recent studies it was shown that seismics was useful to detect CO_2 saturation below 15% and that electrical resistivity was useful to detect CO_2 saturation above 15% (Kim et al., 2013).

Seismoelectric signals are electrokinetically generated by the propagation of seismic waves within a porous material. They can be recorded using a seismic source and electric receivers. The seismoelectric strategy aims to combine the resolution of the seismics to the sensitivity of the electric methods to fluid content. A specific seismoelectric signal, denoted the interfacial response, is expected to be induced at contrasts between rock properties (Garambois and Dietrich, 2002), including different fluids and different fluid-contents. This signal is usually weak compared to the so-called coseismic signal, which is the seismo-electric signal travelling within the seismic wave directly induced by the source. Several authors have investigated the benefits of surface-to-borehole seismoelectric layouts to accomplish efficient measurements of the interfacial response, as opposed to layouts for which both the seismic source and the receiving electrodes are laid at the surface.

The aim of this work is to provide numerical evidence that borehole seismoelectrics can discern carbon dioxide concentrations in a broader range than seismics allow, detecting at the same time salinity contrasts, task up to now fulfilled by geolectrics. The pure SH seismic source considered in the present study could achieve a better resolution than the one obtained through the usual P-driven experiments because of shorter wavelengths.

We start our work by reviewing the most important theoretical concepts of seismoelectrics, and by proposing a possible appropriate field experimental setup. We follow by analyzing shear-wave driven interface responses generated between to two consecutive units saturated with water, using a one dimensional finite element method to approximate the solution to Pride's equations. We study the sensitivity of these responses to contrasts in relevant parameters, such as porosity, salinity and viscosity; and continue by investigating the coseismic waves and interface response amplitudes of tabular media when one layer is partially saturated with carbon dioxide, employing in this analysis different models to take into account this situation in the electrokinetic coupling. Finally, we consider a layered model including a seal layer, in order to simulate a realistic CO_2 deposition site.

2. Theoretical background

The seismoelectric method relies on electrokinetically induced seismic-to-electric energy conversions occurring in fluid-containing porous media. The reader can find a tutorial on electrokinetics in Jouniaux and Ishido (2012).

2.1. Theoretical aspects

When a compressional wave travels through a porous medium, it creates a fluid-pressure gradient and an acceleration of the solid matrix, inducing a relative motion between the ions adsorbed at the grain surface and the counter-ions in the diffuse layer. This charge separation at the scale of the seismic wavelet creates an electrical potential difference known as the streaming potential. The electric field arising from this potential is known as the coseismic wave, as it travels within the passing compressional seismic waves. Therefore coseismic electric fields do not extend outside the seismic waves creating them, and may only help characterize the medium near the receivers. For borehole seismoelectric measurements they give information about the medium in the vicinity of the well (Mikhailov et al., 2000).

Another type of seismoelectric conversions arises when a seismic wave crosses a contrast between mechanical or electrical properties (Haartsen and Pride, 1997; Chen and Mu, 2005; Block and Harris, 2006). In this situation a transient localized charge separation across the interface is created, which acts as a secondary source that can be approximated as an electrical dipole oscillating at the center of the first Fresnel zone (Thompson and Gist, 1993; Garambois and Dietrich, 2002). The resulting electromagnetic (EM) wave is known as the interface response (IR), and diffuses independently from the seismic wavefield: the velocity at which it travels is several orders of magnitude greater than seismic velocities. This IR may provide information about the contrasts in the medium's properties at depth.

The equations governing the coupled seismic and electromagnetic wave propagation in fluid-filled porous media were derived by Pride (1994) by combining Maxwell's equations with Biot's equations for poroelasticity (Biot, 1956a,b). Two coupled transport equations were derived (Eq. 251 and 252 in Pride (1994)):

$$\mathbf{J} = \sigma(\omega)\mathbf{E} + L(\omega)(-\nabla p + \omega^2 \rho_w \mathrm{u}_s) \tag{1}$$

$$-i\omega \mathrm{u}_f = L(\omega)\mathbf{E} + \frac{k(\omega)}{\eta_w}(-\nabla p + \omega^2 \rho_w \mathrm{u}_s) \tag{2}$$

The macroscopic electrical current density $\mathbf{J}$ [A/m^2] is given in Eq. (1) as the sum of the average conduction and streaming current densities, respectively the first and second term of its right-hand side. Both the above equations assume a $e^{-i\omega t}$ time dependence of the propagating wave, where ω [rad/s] denotes the angular frequency. The parameter $\mathbf{E}$ [V/m] denotes the electric field and $\sigma(\omega)$ [S/m] is the frequency-dependent conductivity of the material. Streaming currents may be induced by both the pressure gradient $-\nabla p$, where p [Pa] is the pore-fluid pressure, and the acceleration of the solid frame $\omega^2 \rho_w \mathrm{u}_s$, where ρ_w [kg/m^3] is the density of the fluid (water) and $\mathbf{u}_s$ [m] denotes the solid displacement. The fluid velocity $-i\omega \mathbf{u}_f$ [m/s] is written in Eq. (2) as the sum of electrically and mechanically induced contributions. The frequency-dependent permeability is written as $k(\omega)$ [m^2] and the dynamic viscosity of the fluid is expressed as η_w [Pa s]. The complex and frequency-dependent coupling $L(\omega)$ links Eqs. (1) and (2):

$$L(\omega) = L_0 \left[1 - i\frac{\omega}{\omega_t}\frac{b}{4}\left(1 - 2\frac{d}{\Lambda}\right)^2 \left(1 - i^{3/2} d \sqrt{\frac{\omega \rho_w}{\eta_w}}\right)^2 \right]^{-1/2} \tag{3}$$

In Eq. (3), Λ [m] is a pore geometrical parameter, defined in Johnson et al. (1987), whereas b is a dimensionless parameter defined in terms of the latter, the porosity ϕ, the absolute permeability k_0 and the tortuosity α_∞ as b=$(\phi/\alpha_\infty k_0)\Lambda^2$ and consisting only of the pore-space geometry terms. This parameter b was originally denoted m in Pride (1994). When k_0, ϕ, α_∞ and Λ are independently measured, b is comprised between 4 and 8 for a variety of porous media ranging from grain packing to capillary networks consisting of tubes of variable radii (Johnson et al., 1987). The parameter d [m] denotes the Debye length, while ω_t [rad/s] is the permeability-dependent transition angular frequency between the low-frequency viscous flow and high-frequency inertial flow. Finally, L_0 denotes the electrokinetic coupling which expression we give below. The coupling $L(\omega)$ was studied by Reppert et al. (2001), Schoemaker et al. (2007), Jouniaux and Bordes (2012) and Glover et al. (2012). When this