Seismoelectric interface response signal behaviour in thin-bed geological settings

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SUMMARY

Increasing industrial and societal challenges demand a continuous need for improved imaging methods. In recent years, quite some research has been performed on using seismoelectric phenomena for geophysical exploration and imaging. Like the other methods, the seismoelectric technique also has its drawbacks. Besides the fact that the physical phenomenon is very complex, one of its main challenges is the very low signal-to-noise ratio of the coupled signals, especially the second-order interface response fields. From seismics, it is well-known that anonamously high amplitudes can arise due to amplitude-tuning effects which can occur when a seismic signal travels through a package of thin-layers with appropriate amplifying thickness. Using numerical seismoelectric wave propagation experiments through packages of thin-beds, we show that thin-bed geological settings can improve the signal-to-noise ratio of the interface response fields. Whether a certain package of thin-beds results in a net strengthening or weakening of the signal, is determined by the contrast in and the order of the coupling coefficients of the different thin-layer media. Formulated differently, we show that the seismoelectric method is sensitive to the medium parameters of thin-bed geological structures far below the seismic resolution, and that due to natural strengthening of the seismoelectric interface response signal, the method might be already suitable for certain geological settings.

INTRODUCTION

Increasing industrial and societal challenges demand a continuous need for improved imaging methods. We can think of monitoring enhanced oil recovery procedures, tracing groundwater pollution or imaging of complex geological areas. In recent years, quite some research has been performed on using seismoelectric phenomena for geophysical exploration and imaging (e.g. Pride (1994), Pride and Haartsen (1996), Thompson et al. (2007), Revil et al. (2007), Schoemaker et al. (2012), Sava and Revil (2012)).

Existing geophysical techniques each have their own benefits and drawbacks. For example, acoustic methods provide us with relatively high resolution, but lack sensitivity to for example different fluid contents. Electromagnetic methods do possess fluid sensitivity characteristics, but lack the resolution seismic methods can provide us with. Seismoelectric methods have several benefits compared to these well-established techniques. The phenomenon can be described by Biot's poroelasticity equations coupled to Maxwell's electromagnetic equations (Pride (1994), Haartsen and Pride (1997)). Not only can we obtain seismic resolution and electromagnetic sensitivity at the same time, the seismoelectric method can also provide us with additional, high-value information like porosity and permeability. Two types of seismic-to-electromagnetic coupling can be distinguished: local, co-propagating electric signals inside the seismic wave (the coseismic field) and independently diffusing electromagnetic fields generated at 'interfaces' with contrasting medium parameters (the interface response field (IR) or seismoelectric conversion). Like the other methods, the seismoelectric technique also has its drawbacks. Besides the fact that the physical phenomenon is very complex, one of its main challenges is the very low signal-to-noise ratio of the coupled signals, especially the second-order interface response fields.

From seismics, it is well-known that anonamously high amplitudes can arise due to amplitude-tuning effects which can occur when a seismic signal travels through a package of thin-layers with appropriate amplifying thickness. Reflection coefficients with opposite polarity can constructively interfere with each other when the bed thickness is equal to half the dominant wavelength (Robertson and Nogami, 1984). A logical question that now arises is: Can thin-beds with appropriate thickness also improve the signal-to-noise ratio of the seismoelectric IR fields? Or a different question: can seismoelectric signals provide us with property information of thin-beds below the seismic resolution?

In this abstract we present some initial numerical modeling results simulating seismoelectric wave propagation in thin-bed geological settings.We investigate the enhancing effect of different layer-package thicknesses compared to the dominant pressure- and shear-wavelengths. We will focus on the impact of the amount and thickness of the individual thin-beds within such a package. Finally, the strengthening or weakening of the signal will be related to the coupling coefficient connecting the poroelastic equations to the electromagnetic equations.

THEORY

Let us start with a quick recapitulation of the seismoelectric theory according to Pride (1994). As mentioned, seismoelectric phenomena can be described by Biot's poroelasticity equations (Biot, 1956) coupled to Maxwell's electromagnetic equations. Using the principle of volume-averaging, Pride (1994) derived the set of governing equations for seismoelectric phenomena in fully-saturated porous media. Haartsen and Pride (1997) describe how to use the basic governing equations to describe seismoelectric wave propagation in horizontally layered, radially symmetric, fluid-saturated porous media. When considering seismoelectric phenomena, we can distinguish two types of seismic-to-electromagnetic coupling: the coseismic field and the interface response (IR) field (or seismoelectric conversion).

We will start looking in more detail how these fields can be generated from the point-of-view of a seismic pressure wave. Please note that similar mechanisms hold for shear wave related coupling and the reciprocal electroseismic (electromagnetic-to-seismic coupling) phenomena. First of all, imagine a seis-

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mic pressure wave travelling through a porous, fluid-saturated medium. This wave creates a fluid pressure gradient within the pulse that induces pore fluid flow. The flow transports excess electrical charge in the so-called electrical double layer (Stern, 1924). We refer to the net flow of charge relative to the grains as the streaming electric current (Schoemaker et al., 2012). This induced conduction current leads to the first type of seismic-to-electric coupling: the coseismic field. This coseismic electric field is generated locally inside the passing seismic wave and can therefore only provide us with localized information close to the receivers. It travels along with the seismic wave and hence with seismic velocities. However, when this wave hits an interface with changing mechanical, hydraulic or electrical properties, this results in a local asymmetry in the charge distribution (Schoemaker et al., 2012), therefore creating an effective electromagnetic dipole source at the interface (Thompson and Gist, 1993). This generates an independently diffusing electromagnetic field that will arrive almost instantaneously at the receiver level, since its velocity is several orders of magnitude higher than the seismic wave velocities. These IR field arrivals will therefore show up in seismo-electrograms as more or less horizontal events at one-way seismic traveltime (the seismic traveltime from the source to the interface). These converted fields can provide us with information at depth and are therefore of primary interest when exploiting seismoelectric methods in industry. However, since these fields are second order coupling effects, their signal-to-noise ratio is very low. The main challenge is to boost the signal-to-noise ratio.

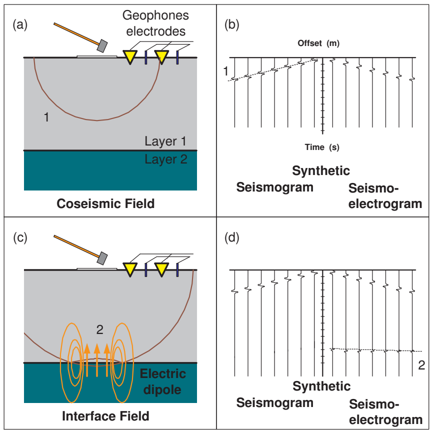

Figure 1: Schematic of a seismoelectric survey (Schoemaker et al., 2012). **(a)** *A seismic pressure wave travels from the source through fluid-saturated porous medium 1, thereby generating a coseismic electric field.* **(b)** *The expected seismic direct pressure wave arrival (left panel) and its coseismic electric field equivalent (right panel)* **(c)** *The pressure wave hits an interface between porous medium 1 and porous medium 2, with contrasting medium parameters. At the interface an effective local oscillating dipole source is created, generating the IR field.* **(d)** *The expected recordings of the IR field in the seismogram (left panel) and seismo-electrogram (right panel).*

From observations in seismics, it is well-known that when a seismic wave travels through a package of thin-layers (with appropriate amplifying thickness) anonamously high amplitudes can arise due to amplitude-tuning effects (Robertson and Nogami, 1984). Can similar improvements in signal-to-noise ratio occur for seismoelectric phenomena? Since the seismoelectric effect is a complex physical phenomenon of which very little is still understood, the exact effect of a seismoelectric wave propagating through a package of thin-beds is unpredictable. However, one can intuitively understand that since the IR fields arrive almost instantaneously at one-way seismic traveltime, an incremental increase in seismic traveltime due to the thickness of a thin-bed might result in constructive interference of recorded IR fields. In other words, when the one-way seismic traveltime is not increasing too much, the generated IR field of the bottom interface of a certain thin-bed might map constructively on the generated IR field of the top interface of the thin-bed. Important questions to ask are of course: what is the sub-seismic resolution limit for seismoelectric sensitivity? Does an increase in the amount of thin-beds necessarily lead to an increase of the IR field signal strength? What parameters play a role in determining whether constructive or destructive interference occurs? As (Widess, 1973) already acknowledges: How thin is a thin-bed? For seismics, based on reflective properties, a thin-bed may be defined as a bed with a thickness that is less than $\lambda_{peak}/8$. Here, λ_{peak} is the dominant wavelength for the seismic velocity of the bed (Widess, 1973). To investigate the effect of bed-thinning on the possible signal strengthening of the IR fields, we will model 3D seismoelectric wave propagation through a laterally invariant, isotropic layer-cake model. We will make use of the analytically based, electroseismic and seismoelectric layered earth numerical modeling code 'ESSEMOD' (Grobbe and Slob (2013), Grobbe et al. (2012)). We will increase the amount of thin-beds in packages of variable thickness. Package thicknesses thinner than, thicker than and equal to the dominant seismic P- and S- wavelengths will be discussed. Different configurations of alternating thin-beds will be considered, to investigate the effect of different coupling coefficient contrasts between the beds.

RESULTS AND DISCUSSION

In order to investigate the effect of bed-thinning on the strengthening or weakening of the IR field, we simulate seismoelectric wave propagation through horizontally layered configurations with different amounts and thicknesses of thin-beds. To be able to fully focus on the effect of the thin-beds we will use a very simple reference configuration consisting of two homogeneous halfspaces (hs) A and B or A and C. For convenience, we will not present all medium parameters but only the effective seismoelectric wave velocities resulting from the chosen medium properties and the corresponding coupling coefficients. These are presented in Table 1. The amount of time-samples is $Nt = 2048$, the time-sampling step $dt = 0.001$ s, the amount of radial frequencies $Nom = Nt/2+1$ and the radial frequency sampling step $dom = 2\pi/(Nt \cdot dt)$ rad$\cdot$ s^{-1}. The wavelet is a causal, first-derivative of a Gaussian with peak frequency of 30 Hz. Let us start with a reference configuration of hs A above hs B. We now define a package of certain thickness PT, that will be inserted in between hs A and hs B. We will consider configurations where PT = 20, 40, 80, 160 m. In addition, we will consider PT = 70 and 105

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Physical quantity	Medium A (top hs)	Medium B (layer or hs)	Medium C (layer or hs)
Fast P-wave velocity	3159.805 m/s	3153.670 m/s	3348.942 m/s
Slow P-wave velocity	2.887-92.958 m/s	3.975-131.091 m/s	5.456-189.623 m/s
S-wave velocity	2110.794 m/s	1952.835 m/s	1886.085 m/s
EM-velocity	31796.337-1005899.697 m/s	4496.681-142233.397 m/s	20109.771-636104.472 m/s
Coupling Coefficient (static)	9.067 $\cdot 10^{-9}$ $m^2 \cdot s \cdot V^{-1}$	2.078 $\cdot 10^{-9}$ $m^2 \cdot s \cdot V^{-1}$	1.653 $\cdot 10^{-9}$ $m^2 \cdot s \cdot V^{-1}$

Table 1: Overview of the wave velocities and coupling coefficients for each of the different media. Note that the slow P-wave velocity and the EM-velocity are frequency-dependent and therefore a velocity range is presented.

m, corresponding to the dominant wavelength of the S-wave and fast P-wave, respectively. According to (Widess, 1973), the minimum seismic thin-bed thickness then reads by definition $\lambda_{peak}/8 = 105/8 = 13.125$m for P-waves and $\lambda_{peak}/8 = 70/8 = 8.75$m for S-waves. The package PT will be divided into an even amount of sublayers Nl. The layers will alternate medium B and medium C or vice versa. We will consider the amounts of sublayers: $Nl = 2$, 4, 8, 16, 32 and for larger PT also $Nl = 64$. By fixing the package thickness and dividing it consistently into a certain amount of sublayers, the bed thickness will change accordingly. In this way both the effects of bed-thickness and amount of beds will be investigated.

Let us start with the configurations A-B-C-B, A-B-C-B-C-B and so on. The reference response is then modeled as hs A above hs B. We consider a Cartesian reference framework, where z is pointing downwards representing depth. We will look at the seismoelectric source-receiver component $E_1^{f_1^b}$, the horizontal electric field component E_1 in the x_1-direction due to a horizontal seismic bulk force f_1^b in the same x_1-direction. The source is located at $z = 100$ m and the receivers are placed at $z = 700$ m. The interface separating the bottom of hs A from the top of the thin-layer package is at $z = 1000$ m depth. Figure 2 shows the results for different package thicknesses PT, whereas each subfigure shows the effect of increasing Nl compared to the reference response. Considering the seismic wave velocities of medium A (see Table 1), the generated IR fields are expected to arrive at one-way seismic time $t = 0.285$ s for the P-wave associated field, and at $t = 0.427$ s for the IR field due to an S-wave. The rest of the visible events represent coseismic wavefields. Looking at Figure 2, several observations can be made. First of all, for the source-receiver combination and medium parameters (coupling coefficients) under consideration, the pressure wave related IR field signal at $t = 0.285$ s is not strengthened or weakened at all due to increasing amounts of thin-beds. On the other hand, the amplitude of the S-wave related IR field at $t = 0.427$ s is generally increasing when the amount of thin-layers increases. Let us now zoom in on specific package thicknesses. At or around a package thickness of 105 m, corresponding to the dominant P-wavelength, there seems to be a maximum strengthening of the S-wave related IR signal of a factor 3. We can also observe that the generated multiple train caused by relatively ’thick’ beds, at low values for Nl and relatively high package thicknesses, is compressed with increasing Nl and correspondingly decreasing sub-layer thickness. In this way all multiples ’map’ at the arrival time of the reference S-wave related IR field. Hence, one can intuitively understand that increasing amounts of layers can lead to an increased IR signal strength. However, one can also argue that as soon as all multiples have been compressed, the maximum signal strengthening has been achieved. Another way to look at this is that further thinning of the sublayers, at a certain point does not improve the signal-to-noise ratio of the IR fields anymore, since the thickness is below the sensitive resolution of the seismoelectric waves. Illustrative examples can be found comparing the signal of $Nl = 32$ with the signal of $Nl = 64$ for $PT = 80$. In general, the convergence seems to occur when the thin-bed thickness reaches a value around 2.5 m. An important anomaly to the general pattern described above, can be observed in $PT = 160$, for $Nl = 2$. In this case the individual bed-thicknesses equals 80 m, which is around the dominant S-wavelength. This observation stimulated P- and S-wave tuning experiments (not presented in this abstract), where the amount of sublayers was increased each with a layer thickness of either the dominant P- or S-wavelength, 105 m and 70 m, respectively. These experiments showed that for both cases, increasing Nl did not make a difference for the amplifying effect. In addition, non-converging multiples could be observed. Let us now look what happens if we change the order of the thin-beds, i.e. looking at configurations like A-C-B-C with reference response hs A-hs C. Except the change in order of the thin-beds, the modeling experiment is identical to the experiment discussed above. Similar observations can be made as in Figure 2, except that now increasing Nl leads to a decreased signal strength of the S-wave related IR field. Looking at the medium properties of media B and C, two main differences can be observed. First of all, the contrast in electromagnetic velocity between medium B and medium A is much larger than between medium C and medium A. Furthermore, the coupling coefficient of medium B is larger than the one of medium C and therefore forms a smaller difference with the highest coupling coefficient of medium A. Intuitively, one can imagine that the contrast in coupling coefficients plays an important role in the signal strengthening or weakening of the IR fields. One can observe that the reference response of hs A-hs C has a higher S-wave related IR field than the reference response of hs A-hs B. However, what is surprising is the fact that additional thin-bed contrasts do not help to boost the hs A-hs C reference response, and do help in strengthening the IR of the reference hs A-hs B.

CONCLUSIONS

Numerical seismoelectric wave propagation experiments through packages of thin-beds have shown that thin-bed geological settings can improve the signal-to-noise ratio of the IR fields. Whether the thin-beds result in an effective strengthening or weakening of the signal, seems to be determined by the contrast in and order of the coupling coefficients of the different thin-layer media. It has been shown that the seismoelectric method is sensitive to the medium parameters of thin-bed geological structures far below the seismic resolution and that the method in addition might be applicable already in specific geological areas due to natural strengthening of the IR fields.

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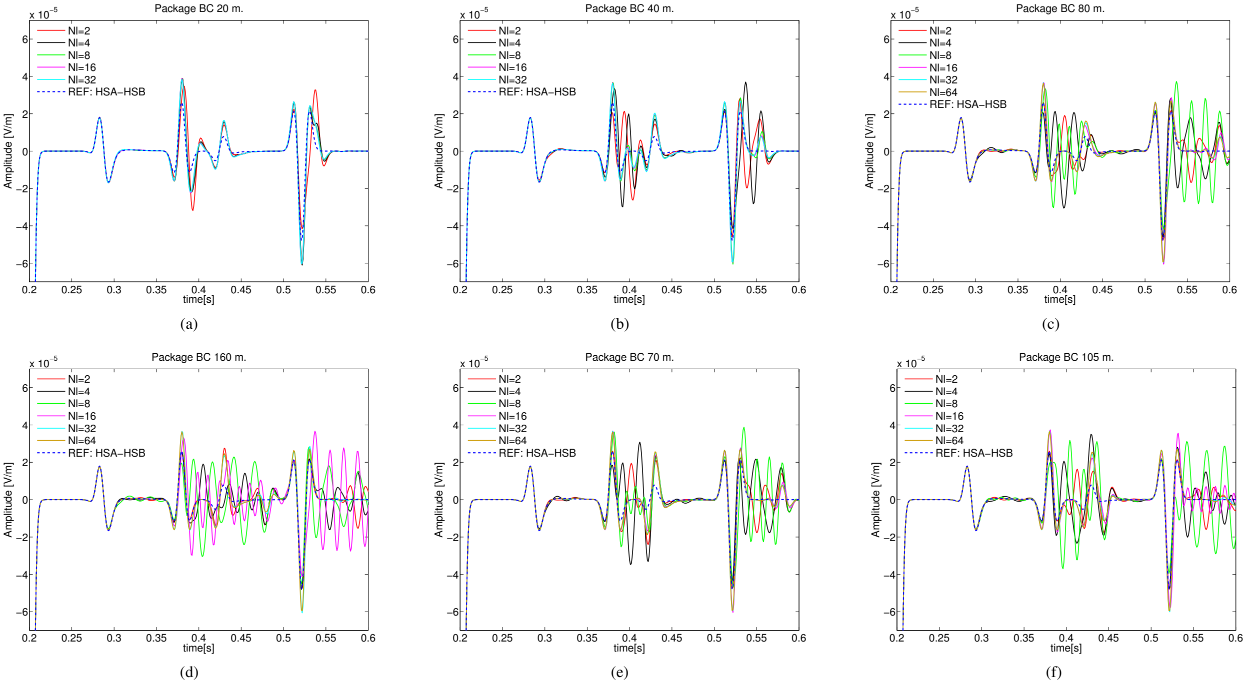

Figure 2: Response for thin-bed geometries of the form A-B-C-B, varying with the amount of layers *Nl* for package thicknesses **(a)** *20 m.* **(b)** *40 m.* **(c)** *80 m.* **(d)** *160 m.* **(e)** *70 m. (dominant S-wavelength)* **(f)** *105 m. (dominant P-wavelength)*

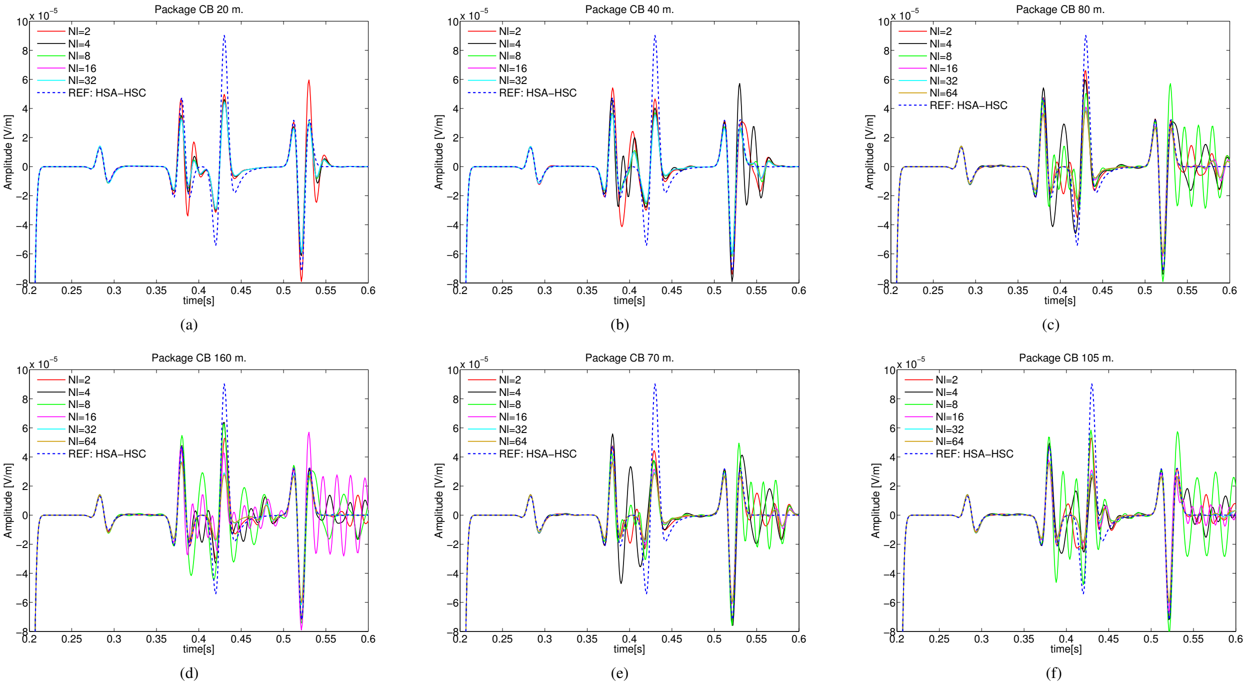

Figure 3: Response for thin-bed geometries of the form A-C-B-C, varying with the amount of layers *Nl* for package thicknesses **(a)** *20 m.* **(b)** *40 m.* **(c)** *80 m.* **(d)** *160 m.* **(e)** *70 m. (dominant S-wavelength)* **(f)** *105 m. (dominant P-wavelength)*

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