Effects of Saturant Conductivity on Seismoelectric Conversion

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Abstract

When a seismic wave propagates in a fluid-saturated porous medium, a seismoelectric field can be induced in the medium due to an electric double layer at the interface between solid and fluid. The strength of the seismoelectric field depends on the characteristics of the double layer and the conductivity of the saturant fluid. In our experiments two kinds of seismoelectric fields, a radiating electromagnetic (EM) wave and a localized electric field, are induced with fractured borehole models. The amplitudes of the seismoelectric signals are recorded when the conductivity of the saturant varies from zero to 27 mS/cm. The results show that when the conductivity increases, the amplitude of the electric signals increases at a low conductivity area and decreases at a high conductivity area. In this paper we investigate the mechanisms of seismoelectric conversion. When a double layer is saturated by charges in fluid, the amplitude of seismoelectric signals is inversely proportional to the conductivity. Conversely, if it is not saturated, the amplitude is directly proportional to the conductivity.

1 Introduction

Seismoelectric conversion has been studied for many years. At the solid-fluid interface of a porous medium or a fluid-saturated fracture, adsorption of an electrical charge to the solid surface creates an excess of mobile ions of opposite charge to that of the fluid. Thus, a double layer is formed on the solid surface (Pride and Haartsen, 1996; Morgan et al., 1989). When a seismic wave propagates in a two-phase medium of solids and fluids, the particle vibration generates a movement of ions in the fluid that induces an electric field, a magnetic field, or an electromagnetic field (Haartsen, 1995). This phenomenon is referred to as seismokinetic or seismoelectric conversion. Inside a homogeneous, porous medium, the seismic wave induces localized seismoelectric and seismomagnetic fields which exist only in the area disturbed by the seismic wave (Zhu et al., 2000). At an interface of material with different properties, such as porosity, permeability, or lithology, the seismic wave induces a radiating seismoelectric or electromagnetic wave, which propagates with light speed and can be received anywhere (Zhu and Toksöz, 1999).

Seismoelectric conversion depends not only on the electric double layer, but also on the conductivity of fluid which saturates a porous medium. Some experiments (Zhu et al., 2000) show part of the relationship between the amplitude of seismoelectric signals and the resistivity of the saturant. When fluid resistivity increases, the seismoelectric amplitude increases. The electric amplitude, however, should be zero if the resistivity of the saturant is infinite and there is no double layer formed at a two-phase interface. Therefore, the proportional relationship does not govern this conversion in the whole range of the fluid resistivity.

Previous studies showed two double layer models (Morgan et al., 1989). Most minerals exhibit a negative surface charge and a zeta potential (Gouy-Chapman model). A seismic wave generates fluid flow, and excess ions in the fluid induce a convection current. In a steady state equilibrium, this convection current is balanced by a conduction current. The measurable potential is induced by these two currents.

In this study we make a borehole model with a fracture between two blocks. An acoustic transducer generates a compressional wave which propagates across the fracture and arrives at the borehole. An electrode records the radiating electromagnetic wave induced at the fracture and the localized electric field induced within the borehole. We record the electric signals as the saturant conductivity varies step by step. The relationship between the amplitude and conductivity is explained qualitatively. These results are helpful for interpretation of an amplitude variation of a seismoelectric conversion.

2 Borehole Model With a Fracture

Figure 1 shows a borehole model with a fracture and a P-wave transducer on a Lucite block. There is a fracture between the Lucite block and rock block with a borehole. The plane P-wave transducer (1.5 inches in diameter) is excited by a square electric pulse with 1000 volts in amplitude and 5 μs in width. The main acoustic energy focuses on the vertical direction (Figure 1). The thickness of the Lucite block and the rock block in the vertical direction are 5 cm and 10 cm, respectively. The borehole diameter is 1.27 cm. During the measurement the plane transducer is fixed on the location shown in Figure 1. The entire system is submerged in a water tank. An electrode made of cable or a hydrophone of 1.0 cm in diameter moves along the water-saturated borehole and records the electric signal or acoustic wave.

The acoustic wave generated by the transducer propagates through the Lucite block and excites a Stoneley wave in the fracture. The Stoneley wave induces a radiating electromagnetic wave at the fracture (Zhu and Toksöz, 2002). When the acoustic wave propagates to the borehole, it induces an electric field on the borehole wall. An electrode in the borehole can receive the electric component of the EM wave induced at the fracture and electric signals induced in the borehole. The EM wave is attenuated by the rock between the fracture and the borehole. The signals received by the electrode in the borehole are recorded by a digital oscilloscope after the signals pass through a preamplifier and filter ranging from 10 to 500 kHz. If the electrode is replaced with a hydrophone, we may record the acoustic wave arriving the borehole.

Figure 2 shows the electric signals recorded by the electrode moving in the borehole.

Comparing the arrival time of the electric signals to that of the acoustic waves, the signal at 22 μs is an EM wave induced on the rock side of the fracture and arriving at the borehole through the rock. The signal at 34 μs is induced by the acoustic waves within the borehole.

Using this borehole model and measurement system, we investigate the effect of the conductivity of the saturant fluid on seismoelectric signals.

3 Measurements With the Model

Previous investigations show that the electric signals induced by a seismic wave are inversely proportional to the saturant conductivity (Zhu et al., 2000). When the conductivity increases, the amplitude of the electric signals decreases. This relationship, in general cases, is correct; however, the amplitude should be close to zero if the conductivity decreases to zero. According to the basic principle of seismoelectric conversion, we know that conversion is based on a double layer due to adsorption of charges in the fluid onto the solid interface. If there is not a charge in the fluid (its resistivity is infinite), a double layer is not formed, and a seismoelectric field cannot be induced. This means the relationship of the inverse proportion is not true at a low conductivity area.

We saturate the fracture and borehole of the model shown in Figure 1 with pump oil. No electric signal was received. Because the oil is isolate fluid, there was no movable charge in the fluid. Thus, a seismic wave cannot induce an electric signal. Next, we built two rock borehole models, one of sandstone, the other of Westerly granite. We cleaned the rock models with pure water several times and saturated the models with pure water in a vacuumed system. We then put the models in the measurement system shown in Figure 1. About an hour later the conductivity of fluid in the tank remained stable. We recorded the electric signals with the electrode in the borehole. When we fixed the electrode at the position of trace 4 in Figure 2 and changed the conductivity by gradually adding tap water or sea water, we were able to record the electric signals. From the amplitude of the radiating EM wave and the localized electric field, we obtain the relationship between the electric amplitude and the fluid conductivity. Because the porosity and permeability of sandstone are larger than granite, the electric amplitude in sandstone is larger than granite.

Figures 3 and 4 respectively show the electric amplitudes in the sandstone and granite borehole models when the saturant conductivity increases gradually.

In our experiment the conductivity is increased to $27 mS/cm$. Figures 3 and 4 show only the conductivity range of 0-2.0 mS/cm. There is a peak of the amplitude in the sandstone borehole (solid line) at the conductivity Cm of 0.25 mS/cm in Figure 3 and a peak at the conductivity Cm of 0.06 mS/cm in Figure 4. In the following discussion, we call the area of the conductivity less or larger than Cm as section I and section II, respectively. The peak in the amplitudes of the EM waves (solid line in the figures) induced at the fracture is not clear. We focus on electrical signals induced in the sandstone and granite boreholes.

When the conductivity is zero (in the oil case), there is no electric signal. In section I, the electric amplitude increases when fluid conductivity increases. After amplitude reaches a maximum, electric amplitudes decrease when fluid conductivity increases. The maximum amplitudes are at a different conductivity in sandstone and granite boreholes. These amplitudes are approximately 0.25 mS/cm for sandstone and 0.06 mS/cm for granite. Below, we discuss the mechanism of seismoelectric conversion in the two sections.

4 Experimental Results

From the solid curves in Figures 3 and 4 we know there are two mechanisms that govern the relationship between seismoelectric conversion and fluid conductivity. Most minerals exhibit a negative surface charge and zeta potential (Gouy-Chapman model) when the surface is in contact with electrolytic pore fluid. Some excess positive ions shear off from the double layer. When an acoustic wave generates a relative motion between fluid and solid, the excess ions move in the direction where pressure decreases and form a convection current i_{conv} (Morgan et al., 1989; Reppert et al., 2001; Reppert and Morgan, 2002):

$$i_{conv} = -\frac{\epsilon\zeta}{\eta} G \Delta P$$

where ϵ is the permittivity of the fluid, G is the geometrical factor, ΔP is the pressure of the acoustic wave, η is the viscosity of the fluid, and ζ is the zeta potential.

If there are enough anions in the fluid, the electric force of the potential generated by the convection current creates a conductive current in the direction opposing the convection current by moving the anions. In steady state equilibrium, i_{conv} is balanced by a conduction current i_{cond}, given by

$$i_{cond} = \sigma G \Delta V$$

where σ is the fluid conductivity and ΔV is the voltage measured across the sample.

Equating these currents leads to the Helmholtz-Smoluchowski equation:

$$\Delta V = \frac{\epsilon\zeta}{\eta\sigma} \Delta P$$

From this equation we know that the voltage of seismoelectric signals is inversely proportional to the fluid conductivity. When conductivity increases, the amplitude of the electric signals decrease, as in section II in Figures 3 and 4. However, the Helmholtz-Smoluchowski equation cannot explain the relationship in section I in Figures 3 and 4.

The Gouy-Chapman model depends on two conditions: there are enough ions in the fluid to create a stable double layer on the interface, and there are both positive and negative ions in the diffuse layer with excess movable positive ions (Pride, 1994).

If not enough anions are adsorbed on the solid surface when the fluid conductivity is very low, there are no more movable anions, and only positive ions in the diffuse layer. In this case, a conductive current i_{cond} cannot be induced by the voltage, as there is only a convection current directly proportional to pressure ΔP. Therefore, the voltage of the electric signals is directly proportional to the fluid conductivity. When the conductivity increases, the positive ions in the diffuse layer and in the convection current increase in section I. If the fluid is an isolate (there is no electric double layer nor any positive or negative ion in the fluid), a convection current cannot be induced.

Different porous media need different amounts of anions in order to saturate the adsorbing layer. Because the porosity of sandstone is higher than granite, more anions are needed to saturate the solid surface of sandstone and thus, the conductivity C_m at the peak voltage in sandstone is larger than granite.

5 Conclusions

We perform experiments in a fractured borehole model to measure seismoelectric signals with an electrode in the borehole. There are two types of seismoelectric fields induced by an acoustic wave excited by a P-wave transducer. The first type is a radiating electromagnetic wave induced at the fracture, and the second type is a localized seismoelectric field induced within the borehole. The experiments show the effects of the saturant conductivity on the amplitudes of seismoelectric fields recorded in the borehole. We gradually change the conductivity from zero to 27 mS/cm with pump oil, pure water, tap water and sea water and record the amplitudes of the two seismoelectric fields. When the model is saturated by oil, no electric signal can be generated at the fracture or borehole. The relationship between the electric amplitude and the saturant (water) conductivity is measured at a different saturant conductivity. Results show that at low conductivity, the electric amplitude increases when the conductivity increases. At a high conductivity area, the electric amplitude decreases when the conductivity increases. On the relationship curve there is a maximum at conductivity C_m, which is related to the zeta potential of the rock. According to the model of a double layer, the amplitude of the electric field is directly proportional to the conductivity before the solid surface is saturated by enough charges, and the amplitude of the electric field is inversely proportional after saturation. Our results show the relationship between seismoelectric conversion and the saturant conductivity, and they provide experimental data to study the electric amplitude variation in seismoelectric conversion.

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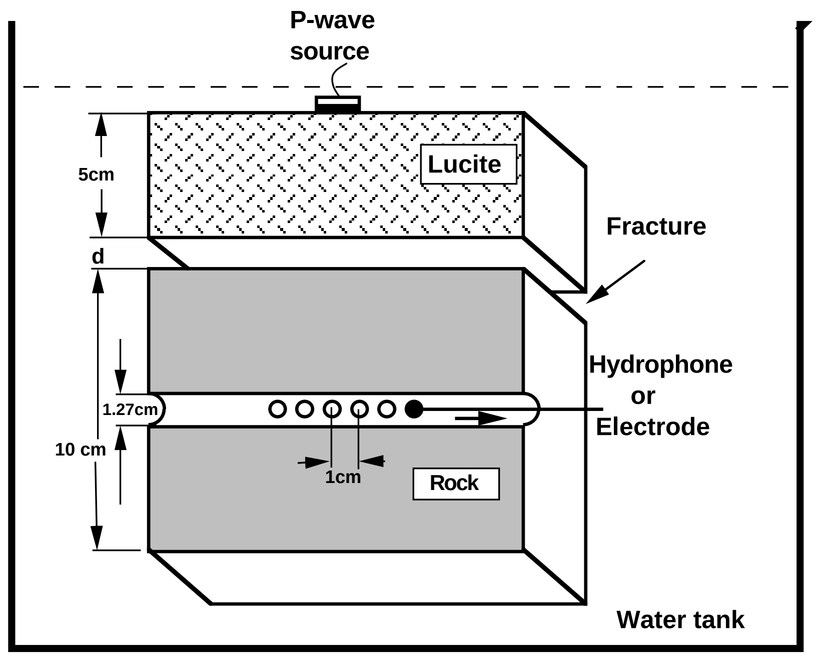

Figure 1: Borehole model with a fracture between rock and Lucite blocks. The model is saturated with water. A plane transducer is fixed on the Lucite block and generates an acoustic wave. A hydrophone or an electrode moves in the borehole and records the acoustic or electrical signals.

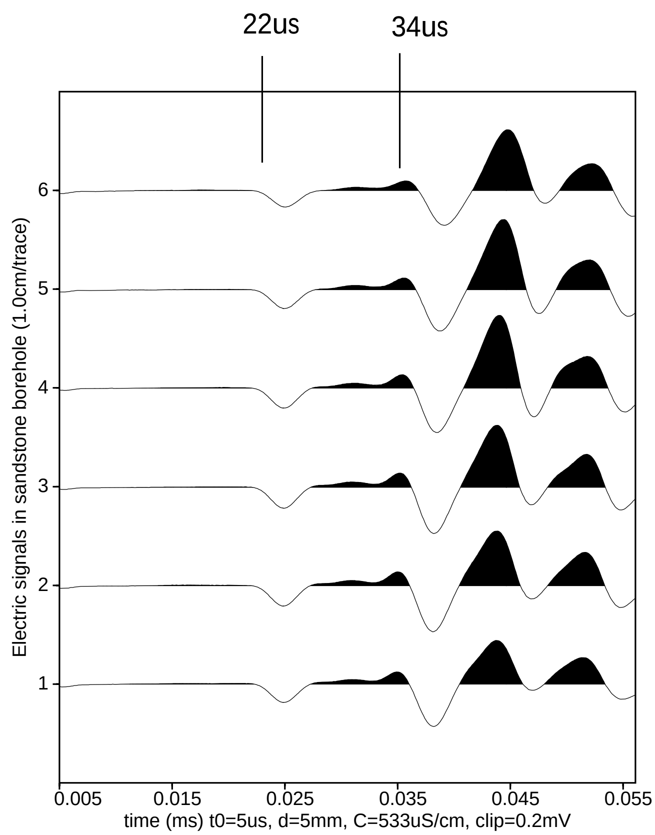

Figure 2: Seismoelectric signals recorded in the borehole in Figure 1. The amplitude in Figure 2a is normalized for each trace by 200 μV. The fracture aperture is 5 mm. The conductivity of the saturant water is about 0.533 mS/cm.

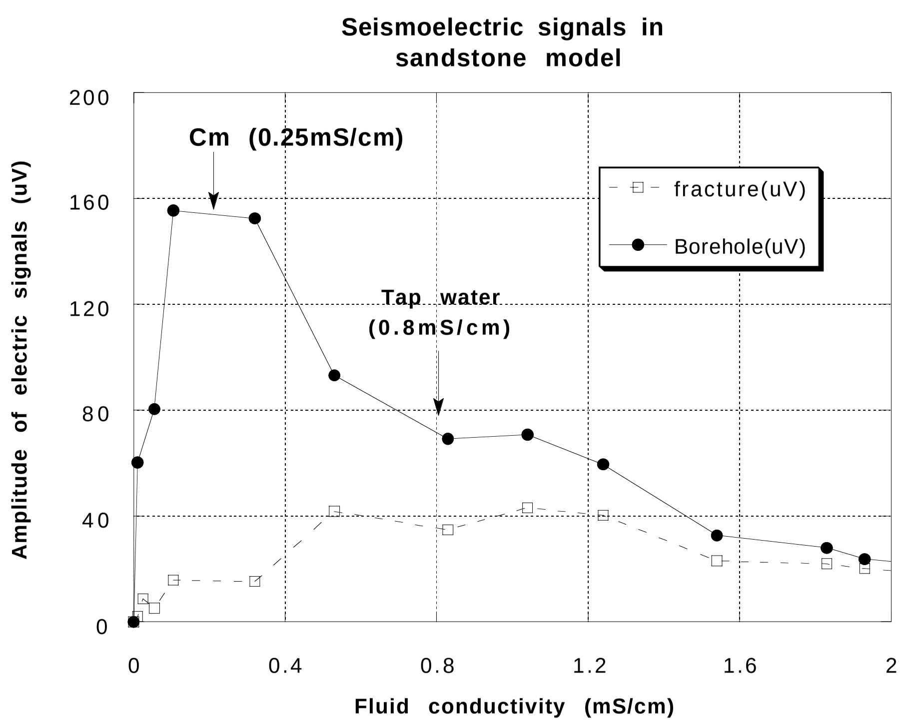

Figure 3: Relationship between water conductivity and the electric amplitude of the EM wave and seismoelectric field induced at the fracture and borehole of a sandstone model. Cm (0.25 mS/cm) is the conductivity where the amplitude is at maximum.

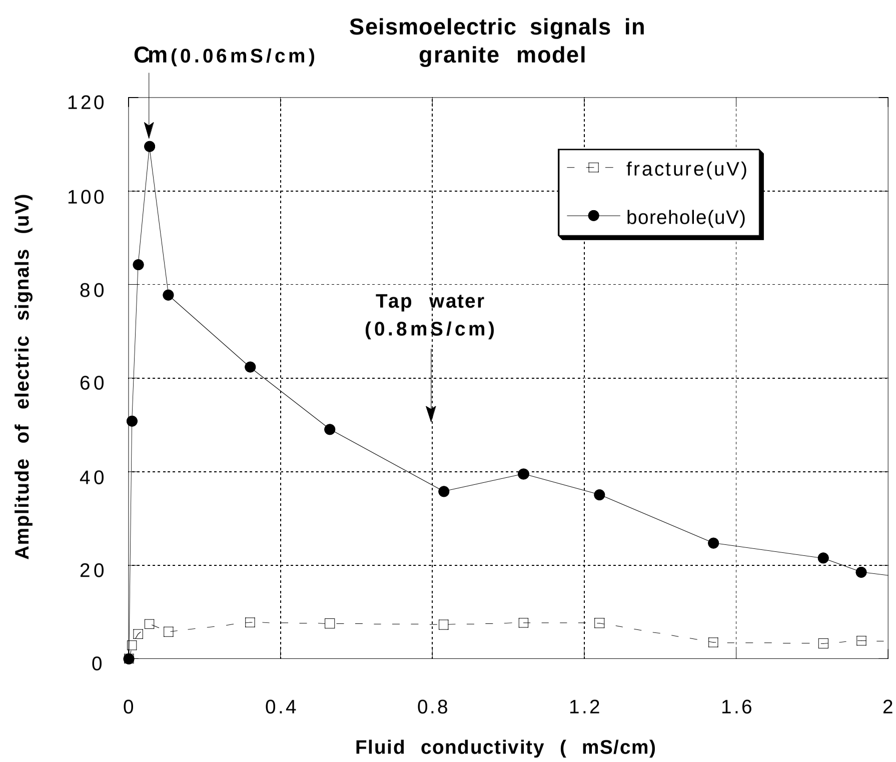

Figure 4: Relationship between water conductivity and electric amplitude of the EM wave and seismoelectric field induced at the fracture and borehole of the granite model. Cm (0.06 mS/cm) is the conductivity where the amplitude is at maximum.