Crosshole Seismoelectric Measurements in Borehole Models With Fractures

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Abstract

Laboratory experiments are performed in cross-borehole models with fractures to investigate seismoelectric conversions in the fractures. A seismic wave propagating in a fluid-saturated porous medium moves ions in the double layer between the fluid and solid and induces an electric field. When there is discontinuity (such as a fracture), the seismic wave induces a radiating electromagnetic (EM) wave. We measure the electric field with an electrode in a borehole, which is induced by an acoustic wave, and investigate the relationship between the electric signal and the fracture aperture with ultrasonic borehole models with a fracture. The experimental results confirm that a radiating EM wave is induced by a guide wave at a fracture between an acoustic source and electric receiver boreholes. The position of a vertical or inclined fracture between two boreholes can be determined with the arrival times of the EM wave and the formation velocity by placing the acoustic source at a different depth and recording electric signals with real or synthetic arrays of acoustic and electric receivers in the second borehole. Because the seismoelectric measurement is based on the seismoelectric conversion induced by acoustic waves, crosshole seismoelectric measurements might be a new means to investigate a fracture between two boreholes more directly than traditional acoustic measurements. It may also be used to construct a tomography with the traveltimes extracted from the electric signal in a borehole similar to traditional crosshole acoustic tomography.

1 Introduction

Determining the interior composition of an object from data measured outside the object has long been a problem of interest in many scientific fields. Tomography is one technique used in noninvasive imaging problems. It uses various types of illuminating energy measurements outside the project of interest to map interior structural properties. There has been success using the noninvasive technique to image medium properties in the medical field. More and

more progress in nondestructive imaging is made using a wide range of materials. The most successful tomographic techniques in the field of seismology have used the arrival times of seismic waves to map the velocities of the subsurface (Lo et al., 1988). Crosshole acoustic tomography has relied on the first arrival travel times and waveforms of the wavefield to map the velocities of the medium between two boreholes (Matarese, 1993; Thompson, 1993).

In a fracture zone, whose size is larger than the wavelength of an acoustic wave, the velocity is lower than normal because the impedance of the zone decreases due to the fractures. Crosshole tomography may show a slow formation zone, but it cannot determine the distribution of fractures in the zone. It is also very difficult to find a single fracture from the crosshole acoustic tomography.

Seismic waves propagating in a fluid-saturated porous-permeable medium induce fluid motion in the pores (Biot, 1956; Plona, 1982). In the presence of ions in the fluid, or double charge layer at the fluid-solid interface, the movement of fluid moves the charges and generates an electric field (Morgan et al., 1989; Pride, 1994). In a homogeneous, porous medium the induced electric field is local and is controlled by rock properties, such as porosity, permeability, lithology, saturant conductivity, etc., and by fluid motion driven by the seismic wave (Zhu et al., 2000). When there is an interface in the medium, the discontinuity of the seismoelectric field gives rise to an electromagnetic (EM) wave radiation (Thompson and Gist, 1993; Haartsen, 1995; Zhu et al., 1999). Seismic wave propagation in a geological medium will produce a local electric field in the homogenous formation, and a radiated EM wave at interfaces between formations. When there is a fracture, the EM radiation is generally stronger than that in the case of formation boundaries.

In the laboratory, Zhu and Toksöz (1999) observed EM wave radiation where fractures intersected a borehole. The EM radiation was strong where fractures were normal to borehole axis (i.e., horizontal fracture) and weak where fractures were vertical. In a VSP-type field experiment, Mikhailov et al. (2000) observed EM waves generated by the incident seismic waves on fractures intersecting the borehole.

Because the seismoelectric wave induced at a fracture is a radiating EM wave, we may measure it outside the fracture area. We may use crosshole seismoelectric measurements to receive the EM wave induced at the fracture and to determine its position between two borehole.

In this paper, we first observe and confirm that a received EM wave is induced at a fracture with a simple fracture borehole model. We investigate the relationship between the amplitude of the EM wave and fracture aperture. Then, we investigate the seismoelectric signatures of vertical or inclined fractures between two boreholes using crosshole measurements in the laboratory at ultrasonic frequencies. In these experiments, acoustic sources are fixed at a point of a borehole or moved in the borehole, and both acoustic and EM waves are reached at the second borehole and received by an acoustic receiver or an electrode. The position of the fracture between two boreholes can be determined from the arrival time of the EM wave.

2 Seismoelectric Conversion at a Fracture

To observe seismoelectric conversion at a fracture, we conducted an experiment with a simple fracture borehole model shown in Figure 1. The velocities and density of the materials used

in our experiment are listed in Table 1. In this experiment, the acoustic source is a plane transducer mounted on Lucite block. The borehole and acoustic and electrical receivers are in a borehole in a sandstone block. The sandstone is saturated with water. The whole model (shown in Figure 1) is placed in a water tank and the borehole and fracture are filled with water.

	Lucite	sandstone	granite
V_p (m/s)	2600	3050	4160
V_s (m/s)	1290	1950	2670
ρ (g/cm ³)	1.18	2.08	2.48

Table 1: Elastic parameters of the materials used in the experiments.

The size of the plane transducer is 3.8 cm in diameter. It is excited by an 1000-volt square electric pulse and $5 \mu\text{s}$ in duration. The main acoustic energy focuses in the horizontal direction (Figure 1) because the source is made of a PZT tube. The widths of the Lucite and sandstone blocks are 5 cm and 10 cm, respectively. The borehole diameter is 1.27 cm. Receivers consisting of a wire electrode and a hydrophone of 1.0 cm in diameter are placed in the water-saturated borehole. It moves along the axis of the borehole.

Figure 1: Borehole model with a fracture between sandstone and Lucite blocks. The model is saturated with water. A plane transducer fixes 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 shows the electric signals (Figure 2a) and the acoustic waves (Figure 2b) recorded in the Lucite-sandstone model with the fracture aperture of 0.5 cm. The amplitudes are normalized by the maximum in the plot, respectively. Figure 2b shows the acoustic signals in the borehole recorded by the hydrophone. The arrival times (about $35.5 \mu\text{s}$) correspond to acoustic waves from the source traveling through the Lucite, water in the fracture, and the

sandstone. In Figure 2a, the large amplitude electrical signal arriving at $34 \mu\text{s}$ is due to the acoustic waves impinging on the borehole. The waves produce the local electric field. The source-to-receiver travel time is that of an acoustic wave. Because of the water gap between the hydrophone and the borehole wall and a phase shift of the hydrophone, there is a time difference of $1.5 \mu\text{s}$ between the arrival time of $34 \mu\text{s}$ (Figure 2a) and $35.5 \mu\text{s}$ (Figure 2b).

Figure 2: Seismoelectric signal (a) and acoustic wave (b) recorded in the borehole in Figure 1. The amplitude in Figure 2a is normalized for each trace by $200 \mu\text{V}$. The fracture aperture is 0.5 cm . The resistivity of the saturant water is about $10 \Omega \cdot \text{m}$.

In Figure 2a, we also observe an electric signal at about $22 \mu\text{s}$ before the acoustic wave arrives at the receiver borehole. This signal should be the electromagnetic wave generated at the fracture by the acoustic wave. After we measured the travel time of the acoustic wave traveling from the acoustic source to the Lucite side in the Lucite block, we know that the arrival time ($22 \mu\text{s}$) of this seismoelectric signal is that of the acoustic wave propagating from the source to the sandstone side of the fracture. The following experiments will confirm that this signal at $22 \mu\text{s}$ is induced at the sandstone side of the fracture. The EM wave propagation time in the sandstone is negligible (nearly zero), since the EM wavelength at 100 kHz is roughly on the order of 1000 m and we are effectively in the electrostatic near field. In this experiment, the resistivity of the saturant water is about $10 \Omega \cdot \text{m}$, which is that of tap water.

To further investigate the seismoelectric signal induced at a fracture, we fixed the acoustic source (the plane transducer) and the electrode in the sandstone borehole at the same horizontal position, and recorded the seismoelectric signals (Figure 3) as we changed the fracture aperture from 0 to 8.82 mm (0 means that the Lucite and sandstone blocks touch). From the arrival times of the electric signals in Figure 3, we can calculate the apparent velocity of the arrivals: 1500 m/s , which is equal to the water velocity.

This experiment shows that the arrival time and the amplitude of the EM wave induced at the fracture increase when the aperture of the fracture increases. The results confirm that the seismoelectric conversion is induced at the sandstone side of the fracture, not at the Lucite side (Wu and Toksöz, 1987), and the EM wave is generated mainly by a Stoneley

Figure 3: Seismoelectric signal recorded in a borehole (Figure 1) when the aperture d changes from 0 (trace 1) to 8.82 mm (trace 8) with an increment of 1.26 mm/trace. The amplitude is normalized by $400 \mu\text{V}$.

wave (a guide wave) excited in the fracture.

When the aperture of the fracture increases, the arrival time of the acoustic wave from the source to the Lucite side of the fracture should be the same time, but the arrival time to the sandstone side is delayed because the distance of water between the Lucite and sandstone sides (aperture) increases. Delaying the arrival time of the EM wave in Figure 3 confirms the EM wave is induced at the sandstone side. This is also the reason why the apparent velocity is equal to the water velocity (1500 m/s).

When aperture increases, the P-wave amplitude decreases due to water attenuation. No shear wave can be excited in the water of the fracture. Only the amplitude of the Stoneley wave excited in the fracture increases with increase in aperture, because the Stoneley wave is a guide wave, and the main energy is focused on the interface between the solid boundary and water. This increasing amplitude of the EM wave in Figure 3 confirms that it is mainly induced by the Stoneley wave excited in the fracture.

3 Vertical Fracture Between Boreholes

Based on the above experiments, we put an acoustic source into a water-filled borehole and conducted crosshole seismoelectric measurements. First, we made a vertical fracture model shown in Figure 4. The fracture is parallel to the two boreholes. A monopole transducer source is located in the granite borehole. The transducer made of a PZT tube is 0.9 cm in diameter and 1.2 cm in length, and is excited by a 1000-volt square pulse with $5 \mu\text{s}$ in width. The main energy of this source is in the horizontal direction (Figure 4). Because the size of the tube transducer is small, the acoustic energy is smaller than the plane transducer used in the previous experiment, although the exciting pulse has the same amplitude. The blocks of granite and sandstone in Figure 4 have the same size, 10 cm by 10 cm by 15 cm and boreholes with 1.27 cm in diameter. The fracture aperture is very large (4 cm) in order

to separate and observe the seismoelectric signals produced at the two sides of the fracture.

Figure 4: Crosshole model with a vertical fracture between granite and sandstone blocks. A PZT tube transducer, as an acoustic source, fixes in the granite borehole. A hydrophone or an electrode moves in the sandstone borehole and records an acoustic wave or electric signal. The diameter of the boreholes is 1.27 cm. The fracture aperture is 4 cm.

When the source is fixed at a certain position, we move an electrode or hydrophone in the other borehole to record the seismoelectric and acoustic fields shown in Figures 5a and 6b. The acoustic wave, propagating through granite, water and sandstone at a horizontal direction, arrives at the sandstone borehole at about $60 \mu\text{s}$ (Figure 5b). In Figure 5a we recorded electric signals at about $45 \mu\text{s}$ and $60 \mu\text{s}$. Calculating the travel times, we confirm that $45 \mu\text{s}$ is the arrival time of the acoustic wave propagating from the source to the surface of the sandstone at the fracture. This means that the seismoelectric signal induced by the acoustic wave at the sandstone surface of the fracture is the source of the electromagnetic wave which propagates from the fracture to the sandstone borehole with an EM wave velocity. We recorded a very weak signal between $20 \mu\text{s}$ and $45 \mu\text{s}$, whose amplitude is much smaller than that after $45 \mu\text{s}$. It is produced at the granite side of the fracture and it is weak due to the low porosity and permeability of granite compared with sandstone. The first arrivals of the acoustic waves around $60 \mu\text{s}$ in Figure 5b are slightly different due to different propagating paths. However, it is difficult to see the moveout in the arrival times of the EM waves (Figure 5a).

We first determine the arrival time of an acoustic wave in the borehole during crosshole acoustic measurements, then determine the seismoelectric wave arriving before that time with crosshole seismoelectric measurements. The fracture position between the borehole can be determined by the arrival time of the EM wave induced at a fracture if the formation velocity is known.

Figure 5: Seismoelectric signal (a) and acoustic wave (b) recorded in the sandstone borehole is shown in Figure 4. The amplitude of the electric signals in Figure 5a is normalized by $25 \mu\text{V}$ for each trace. The fracture aperture is 4 cm.

4 Inclined Fracture Between Boreholes

When a vertical fracture is parallel to boreholes and the acoustic source is fixed at a certain position, the received EM wave induced at the fracture has the same arrival time in the sandstone borehole. To investigate the effect of a dipping fracture between the boreholes, we made a crosshole model with an inclined fracture, shown in Figure 6. The angle between the fracture and horizontal direction is about 70 degrees. A monopole transducer is located in the Lucite borehole, and an electrode is in the sandstone borehole. The aperture of the inclined fracture is 1 cm.

We conducted two experiments to investigate seismoelectric signals induced at the fracture. First, we fixed the source at a certain position in the Lucite borehole, moved the electrode along the sandstone borehole, and recorded electric signals. Then, we fixed the electrode at a certain position in the sandstone borehole and recorded the electric signals when the source moves in the Lucite borehole.

Figure 7 shows the electric signals recorded in the two measurements. Figure 7a shows the signal received by the electrode in the sandstone borehole when the source is fixed at position #2 (Figure 6). Figure 7b shows the electric signal received by the electrode fixed at position #2 (Figure 6) in the sandstone borehole when the source moves in the Lucite borehole.

Figure 7a shows electric signals which have the same arrival time at $32 \mu\text{s}$ when the electrode moves in the sandstone borehole. These signals are radiating seismoelectric signals induced by an acoustic wave at the fracture area corresponding to the horizontal position of the source. The radiating signals propagate with EM wave velocity and arrive at different positions of the sandstone borehole at the same time. After $40 \mu\text{s}$, we record stronger signals which have a different arrival time (Figure 7a). For example, the time for trace 8 is $40 \mu\text{s}$; for trace 1 it is $48 \mu\text{s}$. All of the signals are induced on the sandstone borehole wall by acoustic waves propagating through different paths across the fracture and arriving at the borehole. Because the velocities of Lucite and sandstone are different, the arrival times are different.

Figure 6: Crosshole model with an inclined fracture between Lucite and sandstone blocks. An acoustic transducer fixes or moves in the Lucite borehole and generates an acoustic wave. An electrode fixes or moves in the sandstone borehole and records electric signals. The angle between the fracture and the horizontal direction is about 70 degrees. The horizontal distance at #1 from the Lucite borehole to its fracture side is 5 cm and that from the sandstone borehole to its fracture side is 6 cm. The distance between the two boreholes is about 12 cm. The fracture aperture is 1 cm.

Figure 7: Seismoelectric signals recorded by the electrode in the sandstone borehole (Figure 6) when: (a) the source is fixed at position #2 in the Lucite borehole and the electrode moves from position #1 to #8 in the sandstone borehole. The amplitude is normalized by $25 \mu\text{V}$. (b) the source moves from position #1 to #8 in the Lucite borehole and the electrode fixes at position #2 in the sandstone borehole. The amplitude is normalized by $14 \mu\text{V}$.

When the source moves along the borehole with the same increment (1.0 cm in this experiment), the increments of the horizontal distance from the source to the fracture are identical. Therefore, the arrival time of the main acoustic energy from the source to the fracture should be linear. From Figure 7b, before signals with high amplitude, we observe a seismoelectric signal with smaller amplitude whose arrival time is linear. The velocity of the signal is about 2600 m/s from its slope. This velocity is a P-wave velocity of Lucite. From the first arrival (25.5 μ s) in trace 1, the fracture aperture (1 cm), and the velocities (2600 m/s in Lucite and 1500 m/s in water), we calculate that the distance at position #1 from the borehole to its fracture side is 4.9 cm, close to the real distance of 5 cm. From the time difference (10.2 μ s) between the first arrivals of traces 1 and 8, the vertical distance (7 cm) between traces 1 and 8, and the Lucite velocity (2600 m/s), we calculate that the inclined angle of the fracture is 69.2 degrees. Therefore, if the velocity of the formation between the source borehole and the fracture is known in crosshole seismoelectric measurements, the 2-D fracture position, including distance, dip angle, and direction, can be determined directly from the radiating seismoelectric signals induced at the fracture.

5 Conclusions

In this paper, we introduced experimental studies of crosshole seismoelectric measurements with a fracture between the source and receiver boreholes. When an acoustic source in a borehole generates an acoustic wave, an electrode receives electric signals that are induced by the acoustic wave at a fracture and on the borehole wall. Our experiments also investigated the effect of a fracture aperture on the seismoelectric signals and measurements in crosshole models with a vertical or inclined fracture between two boreholes.

Our experiments confirm that seismoelectric conversion at a water-saturated fracture produces a radiating EM wave which can be received at a receiver borehole. The amplitude of the EM wave induced at the fracture not only depends on the fluid conductivity, but also is related to the aperture of the fracture, because the EM wave is mainly induced by the Stoneley wave excited in the fracture. The experiment results in vertical and inclined fracture models show that the crosshole seismoelectric measurements can more directly and accurately measure the fracture between two boreholes and also determine its 2-D position than the crosshole seismic tomography, which is not sensitive to a single fracture.

The crosshole seismoelectric measurements can record not only the EM wave induced at a fracture, but also the electric signals generated by the seismic wave arriving the receiver borehole. This means that the crosshole seismoelectric measurement can construct a tomography image with the travel times extracted from the seismoelectric signals in the borehole. Therefore, crosshole seismoelectric well logging might be a new means to explore the formation and fracture between two boreholes.

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