EXPERIMENTAL STUDIES OF ELECTROSEISMIC CONVERSION IN A FLUID-SATURATED POROUS MEDIUM

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ABSTRACT

The coupling between seismic and electromagnetic waves in a fluid-saturated porous medium is essentially controlled by the electrokinetic effect. The inverse effect of the seismoelectric conversion, the electroseismic conversion, is investigated experimentally in the laboratory. The electric field induces movement of the ions in a pore fluid relative to the solid matrix. The interaction between the pore fluid and the solid matrix generates acoustic waves known as electroseismic waves. Our studies confirm experimentally that the electroseismic conversion at ultrasonic frequencies is the electrokinetic effect in nature. In measurements with a homogeneous rock cylinder, P- and S-wave transducers receive, respectively, the P- and S- components of the extensional and flexural waves generated by an electric pulse with ring or parallel electrodes when the electrodes are on the surface or inside a porous medium. The electroseismic waves are measured in layered models, made of sandstone or artificial materials, to determine the area where the electroseismic waves are generated. Further experiments with the layered model investigate the relationship between electroseismic conversion and the conductivity of the fluid-saturated medium or the pore fluid. When fluid conductivity increases, the amplitude of the electroseismic wave increases. Experimental results show that electroseismic conversion is different from the piezoelectric effect of quartz grains in sandstone and is closely related to the relative motion between the fluid and the solid. The results also eliminate the possibility that the electroseismic wave is generated by a spark of a high-voltage pulse. Electroseismic waves can be generated at low voltage and increased continually with the voltage, without a big voltage jump similar to the spark in an isolated material. Our results confirm the existence and measurability of electroseismic conversion in porous formation at ultrasonic frequency ranges. Therefore, electroseis-

mic measurements may be an effective means to investigate the pore fluid flow and rock properties.

INTRODUCTION

In a porous medium most grain surfaces that are in contact with a fluid electrolyte acquire a chemically-bound surface charge that is balanced by a diffuse distribution of mobile counter ions in a thin fluid layer surrounding each grain. The bound- and diffuse-charged layers together are known as the electric double layer (Broz and Epstein, 1976; Cerda and Kiry, 1989; Chandler, 1981; Ishido and Mizutani, 1981; Kozak and Davis, 1989). If the counter ions of the diffuse layer move by an electric force, the fluid will move also. The relative movement and interaction between the fluid and the solid matrix generate seismic vibration and mechanic waves (Haartsen, 1995; Haartsen and Pride, 1996; Morgan *et al.*, 1989).

In this paper, we study the electroseismic waves generated by an electric pulse in Berea sandstone cylinder models, confirming that electroseismic conversion exists in natural, fluid-saturated porous rocks. We investigate the electroseismic waves generated by the electrodes on the surface of or inside the porous medium with a layered model made of Lucite and epoxy-glued sand. The relationships between the saturant conductivity and the electroseismic conversion, and the effects of the amplitude and polarization of the electric pulse on the electroseismic conversion, are studied experimentally.

EXPERIMENT IN A CYLINDER MODEL

In our experiments, a high-voltage (50–1000 V) electric pulse, as an exciting source, is applied to a fluid-saturated porous medium through electrodes with different shapes. The round or square cylinder model is made of natural Berea sandstone. Ring or parallel electrodes are attached on one side of the cylinder and connect to the high-voltage pulse. A compressional (P-) or shear (S-) transducer is fixed on the other side and receives the seismic waves.

Figure 1a is a diagram of the measurement system and the rock cylinder with ring electrodes. When the high-voltage pulse connects with the nearest electrodes, the transducer measures and records the compressional waves (Figure 1b) on the other side of the cylinder. From the acoustic waveforms in Figure 1b, we see that the closer the exciting area is to the transducer, the earlier the arrival time and the bigger the amplitude of the wave. The frequencies of the waves are almost the same. This means that the electroseismic waves are generated by the electric field along the axis in the area between the two electrodes. This wave is an extensional wave propagating along the axis. Because the length of the exciting area is the same during the course of the experiments, the frequency of the electroseismic waves will be constant.

Figure 2a shows the Berea sandstone cylinder model with parallel electrodes. Two electrodes of the conducting glue are on the sides of the square cylinder. A shear wave transducer is fixed with shear wave coupling on the other side; its polarization can be changed in the horizontal plane. When the electrodes are connected to a high-voltage pulse generator, an alternate electric field is excited in the direction perpendicular to the axis of the cylinder, and the shear components of the generated electroseismic waves are received by the S-wave transducer at three polarizations (Figure 2b). To check the phases of the waveforms, the influences of the high-voltage pulse (the first one-and-a-half circles) remain in the plot and have the same arrival times, amplitudes and phases. Not only the amplitude, but also the phase of the electroseismic waves vary with the polarization of the shear transducer. This means that the electroseismic wave is generated in the area between the electrodes and propagates as a flexural wave along the axis of the cylinder. The particle motion is perpendicular to the axis and parallel to the exciting electric field.

EXPERIMENT IN A LAYERED MODEL

To study the electroseismic wave generated by the electrodes inside a porous medium, we made a layered model with a Lucite block and epoxy-glued fine sand where some electrodes are buried. Some parameters of the glued sand and Lucite were listed in Zhu *et al.* (1997). The reason for using the Lucite block is to delay the arrival time of the electroseismic wave and to avoid the strong electronic influence of the high-voltage pulse.

When the electrodes are on the surface of the glued sand and excited by an electric pulse (Figure 3a), and the P-wave transducer moves along the the Lucite surface with an increase of 2 cm/trace, the transducer receives the electroseismic waves shown in Figure 3b. We replace the electrodes with a P-wave source transducer and record the acoustic field on the Lucite (Figure 4a). Comparing the electroseismic waves (Figure 3b) with the acoustic waves (Figure 4b), we see that they have the same arrival time and similar amplitude variation. This means that the electroseismic wave is generated in the fluid-saturated porous medium near the electrodes and propagates as an acoustic wave in the model.

If the electrodes are at the same horizontal level (Figure 5a), but the spacing between the negative and positive electrodes varies, the P-wave transducer generates electroseismic waves (shown in Figure 5b) when the spacings are 14 cm, 10 cm, 8 cm, 6 cm, and 4 cm, respectively. When the spacing decreases, the strength of the electric field between the two electrodes increases and the generated electroseismic wave becomes stronger. Although the distances between the center of the electrodes and the transducer are the same, the arrival times of the electroseismic waves (Figure 5b) are different. This means that the depth or area where the electroseismic wave is generated increases or is closer to the transducer when the electrodes are closer to each other and the strength of the electric field increases. If the spacing of the electrodes is fixed at different horizontal levels (Figure 6a), the electroseismic waves (Figure 6b) are almost the same. However, the arrival time and the amplitude vary with the depth of the electrodes. From Figure 6b we calculate the velocity of the electroseismic wave in a fluid-saturated porous medium (glued sand), which is the P-wave velocity.

The above experiments with the layered model confirm that the electroseismic wave is generated by the electric field between the electrodes and, as an acoustic wave, propagates in the medium.

PROPERTIES OF ELECTROSEISMIC CONVERSION

The above results show that the alternate electric field induces the relative motion between the pore fluid and the solid matrix in a fluid-saturated porous medium. Their interaction generates an acoustic wave known as an electroseismic wave. This phenomenon is essentially the conversion between electrical and mechanical energies.

To investigate the properties of the electroseismic conversion, we perform additional experiments with a Berea sandstone layered model (Figure 7). The spacing between the two centers of the electrodes is 8 cm. The acoustic receiver is a P-wave transducer. With this model we change the amplitude and the polarization of the exciting electric pulse, or the conductivity of the saturant, and record the electroseismic waves to investigate the relationship between the electroseismic wave and the exciting pulse or the conductivity of the pore fluid. Experiments also show the difference between the electroseismic conversion and the piezoelectric effect or electric spark.

To study the relationship between the electroseismic conversion and the electric conductivity of the porous medium, we cleaned the Berea sandstone block many times with pure water in a vacuum system. We can then change the conductivity of the water-saturated sandstone by changing that of the saturant water. Our experiments recorded the electroseismic waves generated by the same electric pulse in the layered model saturated by water with a different conductivity. Figure 8 shows the relationship between the normalized amplitude of the electroseismic wave and the conductivity of the saturant (water). When the conductivity increases, the amplitude of the electroseismic wave also increases. The opposite occurs in seismoelectric conversion (Zhu and Toksöz, 1996), where the amplitude of the seismoelectric signal generated by a seismic wave decreases when the conductivity of the saturant increases. This result also shows that the electroseismic conversion is closely related to the pore fluid in the medium, because the interaction of the pore fluid flow on the solid matrix generates the electroseismic wave.

The principle of electroseismic conversion is completely different than that of the piezoelectric effect. There are many quartz grains in sandstone. When an electric field affects these grains, it generates an acoustic wave due to the piezoelectric effect of the quartz. The quartz grains are very small and arranged randomly, thus the generated acoustic wave is very weak or unmeasurable. We record the piezoelectric acoustic wave generated by an 800 V electric pulse in a dry sandstone sample shown in Figure 7, and compare it with the waves generated by the same pulse in the sandstone saturated with water of 400 μS in conductivity (Figure 9). We see that the acoustic wave due to the piezoelectric effect is very weak compared with that of electroseismic conversion.

The principle of electroseismic conversion is also different than that of an electrical spark. When the voltage between two electrodes in an isolated medium increases to a certain value, the medium may be electrically punctured, and a strong temporal current passes through the medium and generates a spark and sound, resembling lightening and thunder in the sky. The spark, caused by the sudden change of the electric property of the medium, happens in an instance or does not vary continually with the voltage. Figure 10 shows the relationship between the amplitude of the electric pulse and the normalized maximum amplitude of the electroseismic wave when the pulse amplitude varies step by step from 100 V to 1000 V in the model shown in Figure 7. In the voltage range of our experiments, the amplitude of the generated electroseismic wave varies continually with that of the electric pulse. It is clear that the electroseismic wave can also be received at a lower voltage range (100–200 V). This means that the electroseismic conversion is not an electric spark. Electroseismic conversion does not change the chemical properties of the medium and can only generate an ion movement in the pore fluid. Electric signals with any amplitude can induce electroseismic conversion and the difference is only in the amplitude of the generated electroseismic waves.

CONCLUSIONS

The experimental results discussed here show that electric signals can generate electroseismic waves with different modes in water-saturated cylinders or layered models. The basic principle of electroseismic conversion is based on the motion of the ions in pore fluid under the forces of an electric field. This movement induces fluid flow relative to the solid matrix. The interaction between the fluid and the matrix generate seismic waves that propagate in the medium.

Electroseismic conversion relates not only to pore fluid flow but to the conductivity of the fluid as well. The more ions there are in the pore fluid, the larger the amplitude of the electroseismic wave generated by the same electric pulse. This phenomenon is opposite to that of seismoelectric conversion, where more ions would counteract the current of the seismoelectric conversion.

The results of the experiment show that the mechanism of the electroseismic conversion is completely different from that of the piezoelectric effect or electric spark. Comparing the electroseismic conversion, the piezoelectric effect is very weak due to the random arrangement of the quartz grains in rocks. The continual variation of the electroseismic conversion with the amplitude of the electric pulse shows that it is not an electrical spark. The measurement of the electroseismic conversion would be an effective method to explore pore fluid flow and some properties of porous formation.

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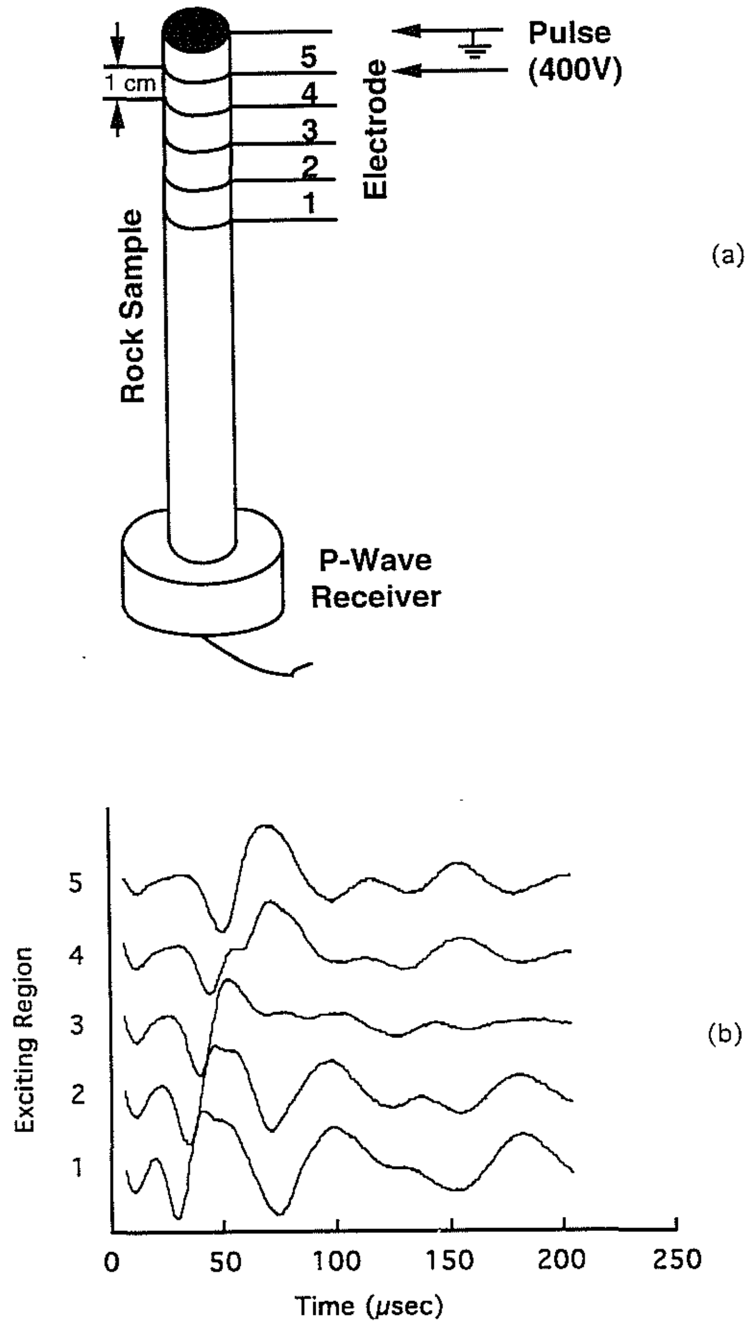
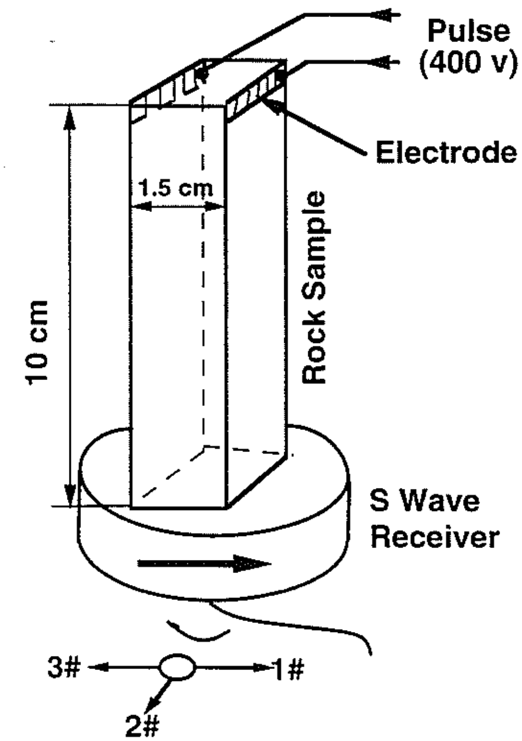


Figure 1: Diagram for measuring the electroseismic waveform generated by an electric pulse with ring electrodes (a), and the electroseismic waves (b) received by the P-wave transducer.



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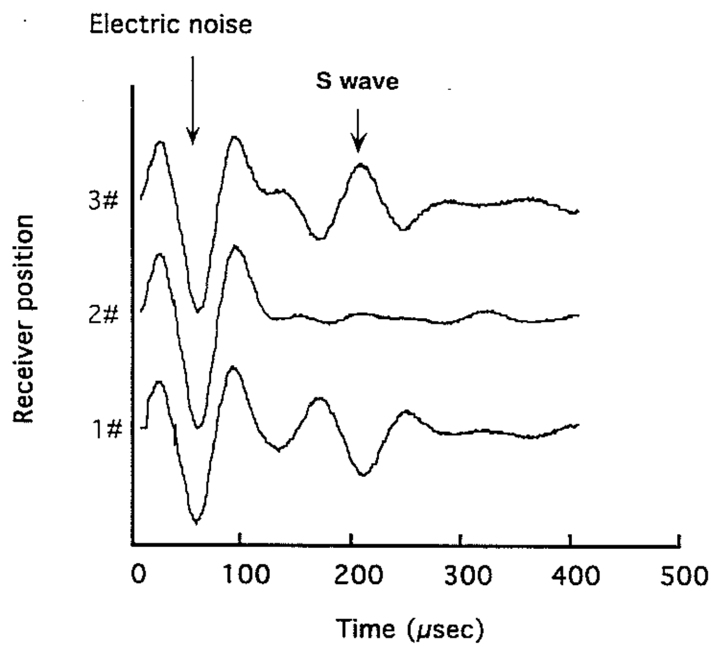
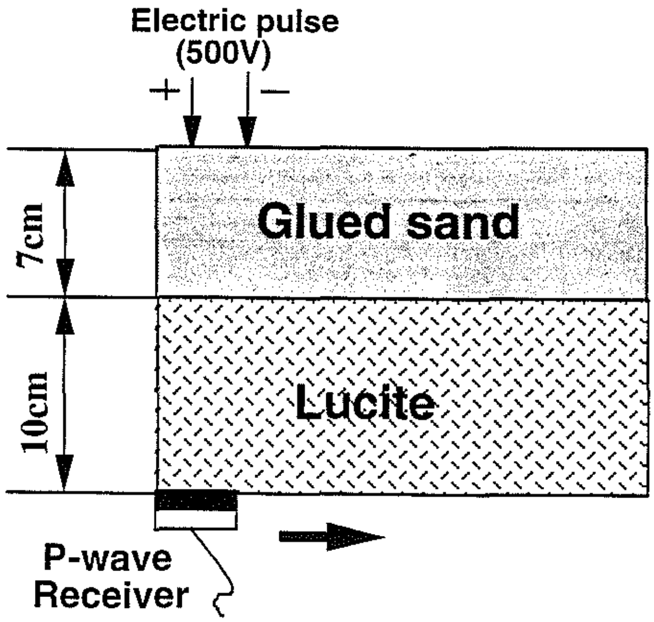


(b)

Figure 2: Diagram for measuring the electroseismic wave generated by an electric pulse with parallel electrodes (a), and the electroseismic waveforms (b) received by the S-wave transducer when its polarization is at #1, #2, and #3 positions.



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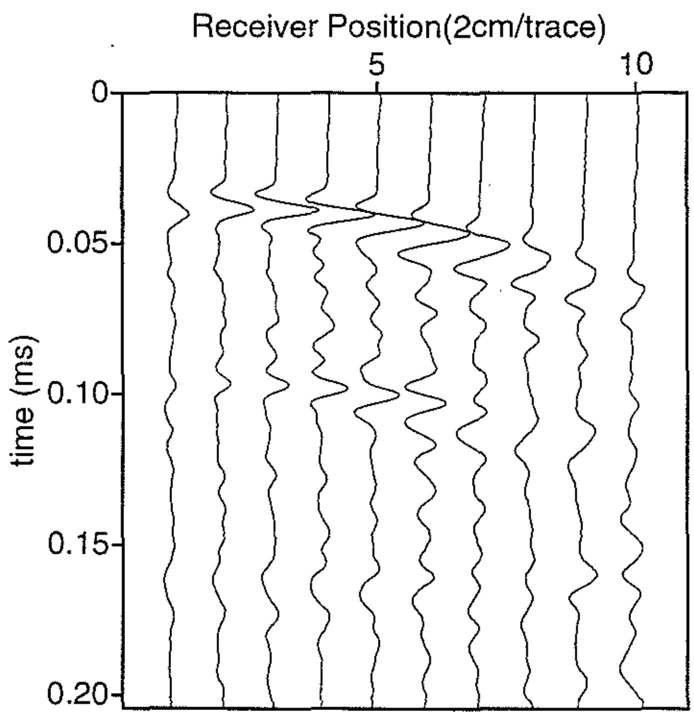
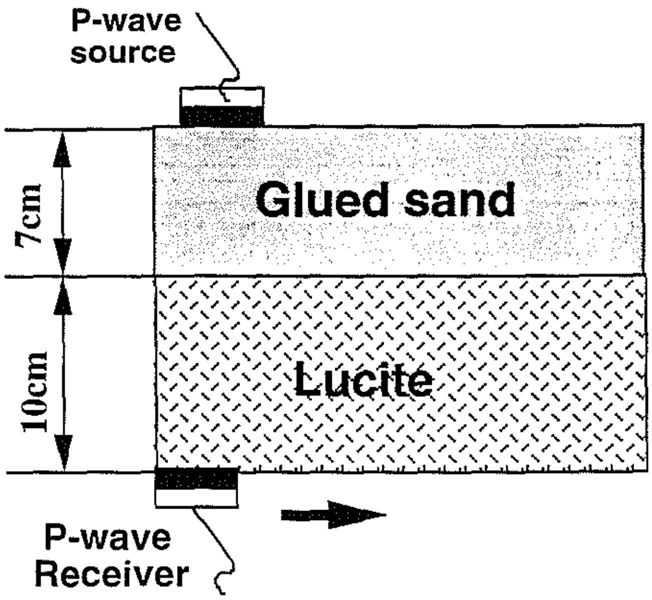


(b)

Figure 3: Glued-sand layered model (a) and the electroseismic waveforms (b) recorded by fixing the electrodes on the top surface and moving the P-wave receiver with 2 cm/trace. The amplitude is normalized by the maximum in the plot.



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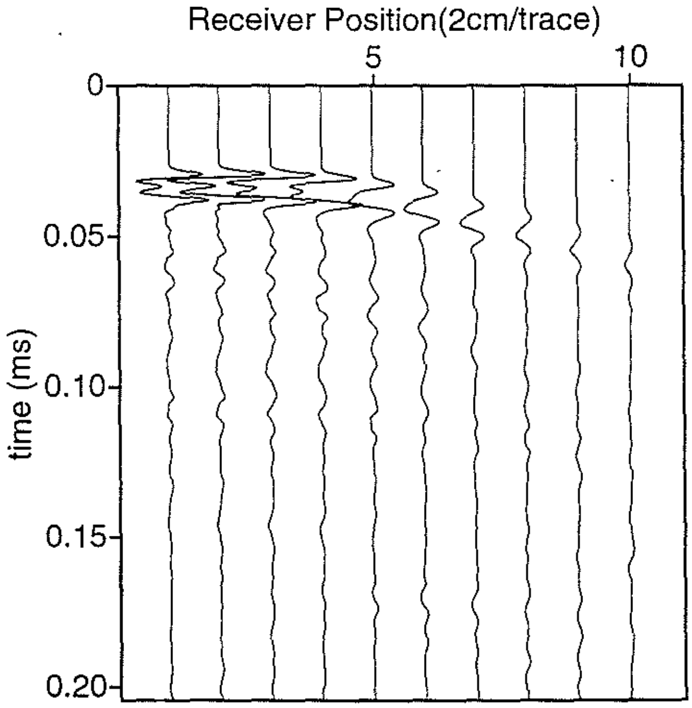


(b)

Figure 4: Glued-sand layered model (a) and the acoustic waveforms (b) recorded by fixing the source transducer on the top surface and moving the P-wave receiver with 2 cm/trace. The amplitude is normalized by the maximum in the plot.

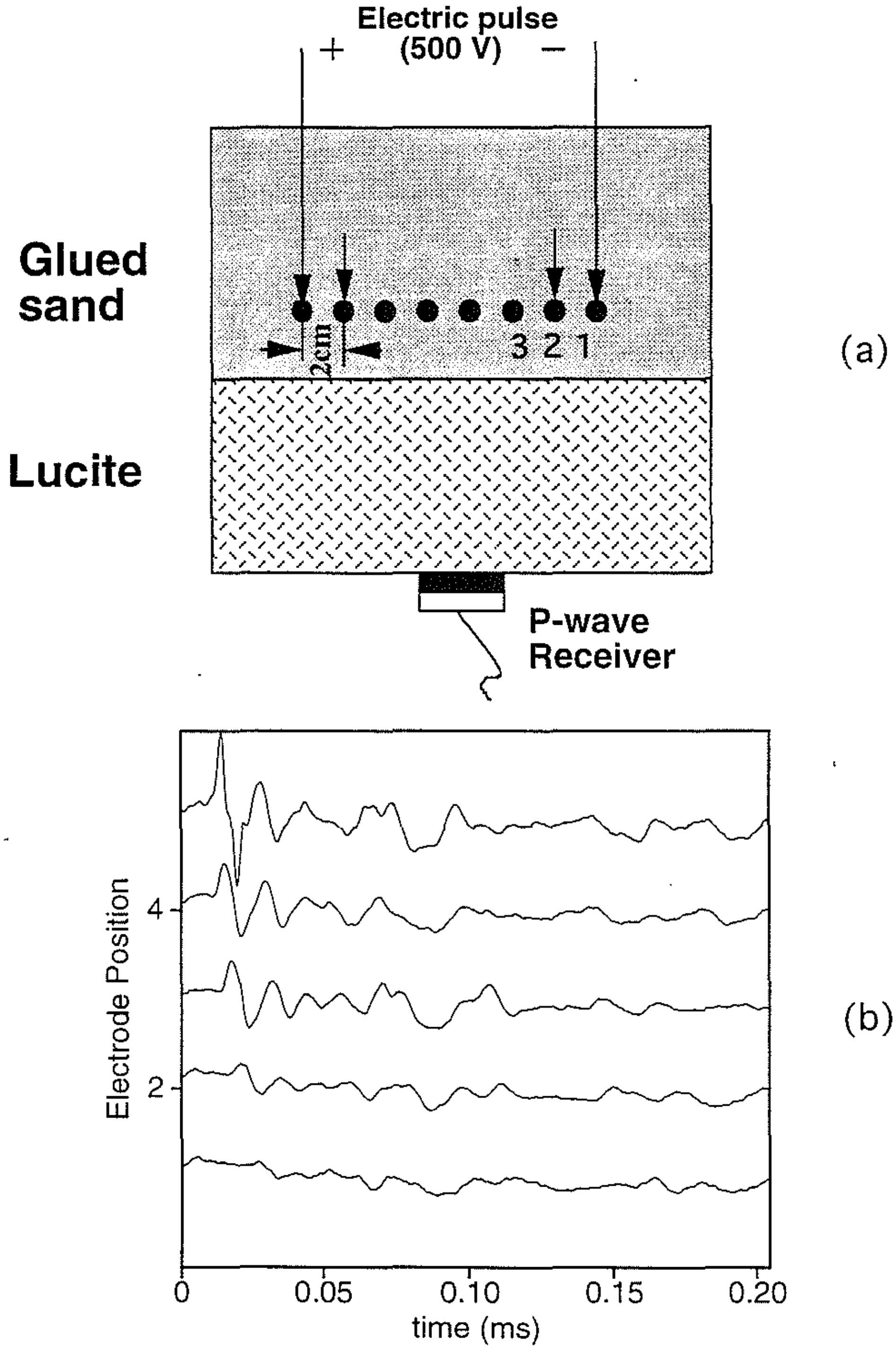
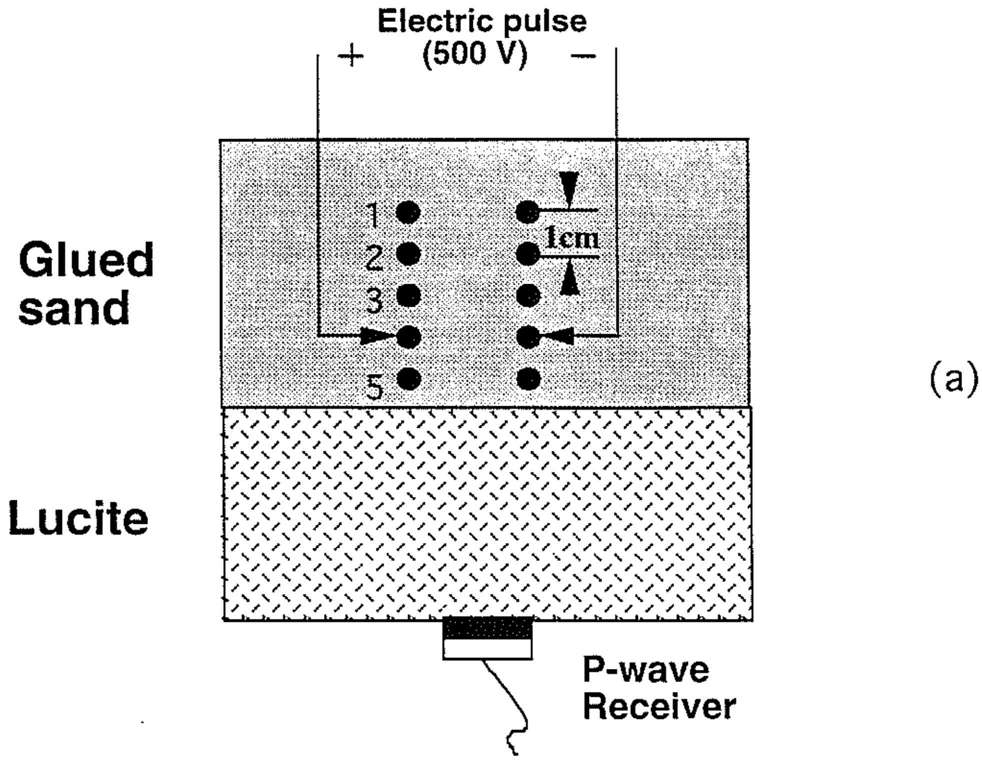


Figure 5: Glued-sand layered model (a) with horizontal electrodes inside the glued sand and the electroseismic waveforms (b) when the spacing of the electrodes varies from 14 cm to 4 cm with 4 cm/trace.



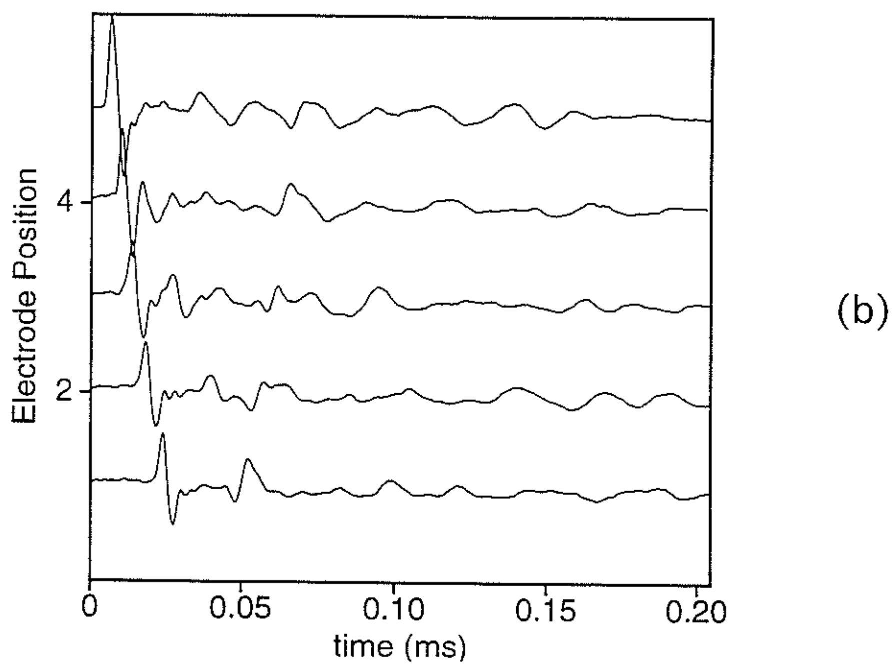


Figure 6: Glued-sand layered model (a) with horizontal electrodes inside the glued sand and the electroseismic waveforms (b) when the spacing of the electrodes varies with 1 cm/trace.

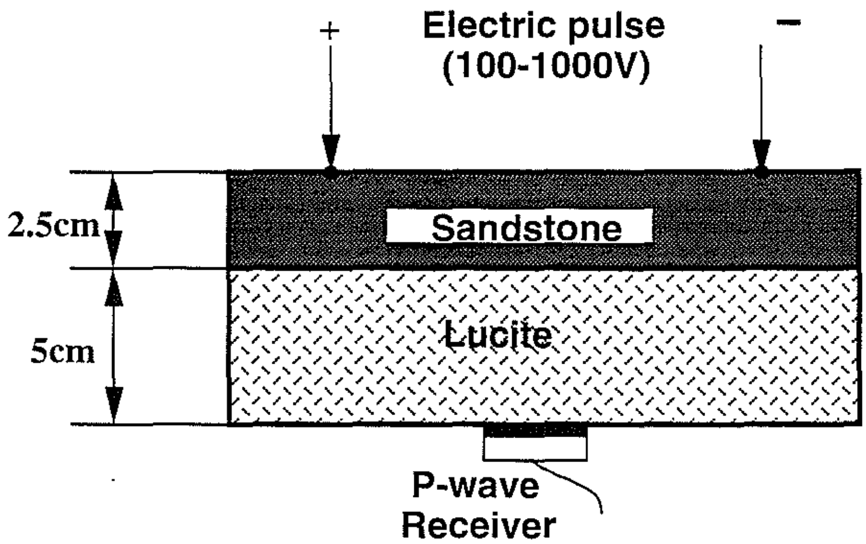


Figure 7: Sandstone layered model.

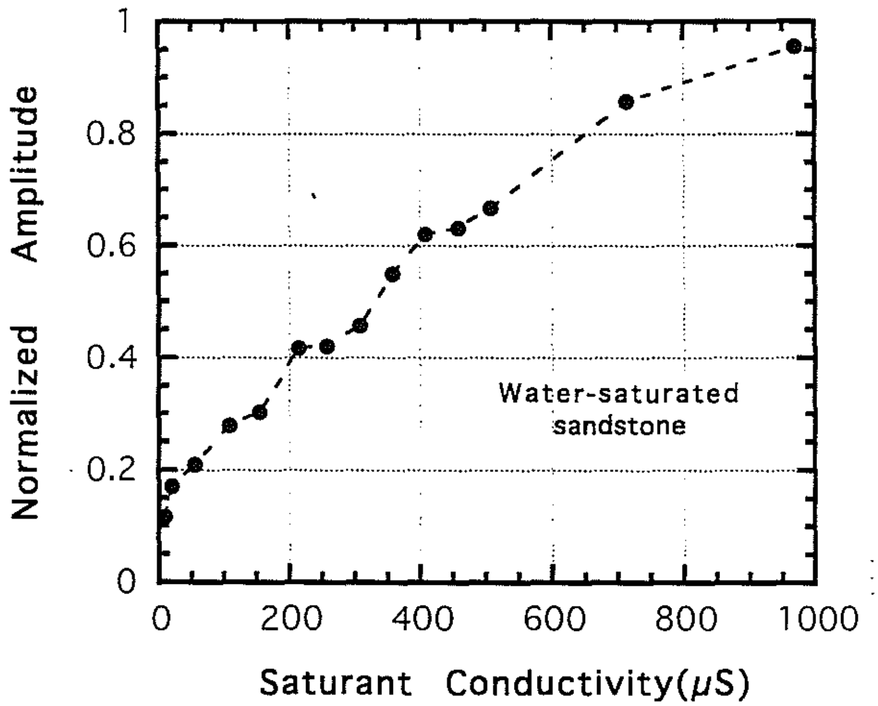


Figure 8: Relationship between the saturant (water) conductivity and the amplitude of the electroseismic waveforms in the sandstone layered model.

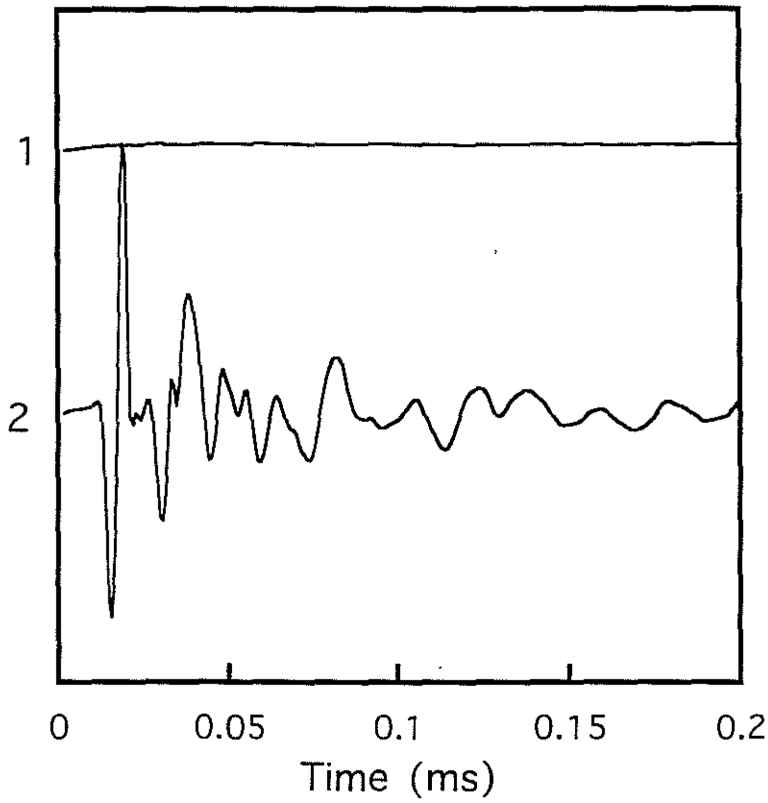


Figure 9: Waveforms recorded in the sandstone layered model when the sandstone is dry (1) or saturated (2) with water of 400 μS in conductivity.

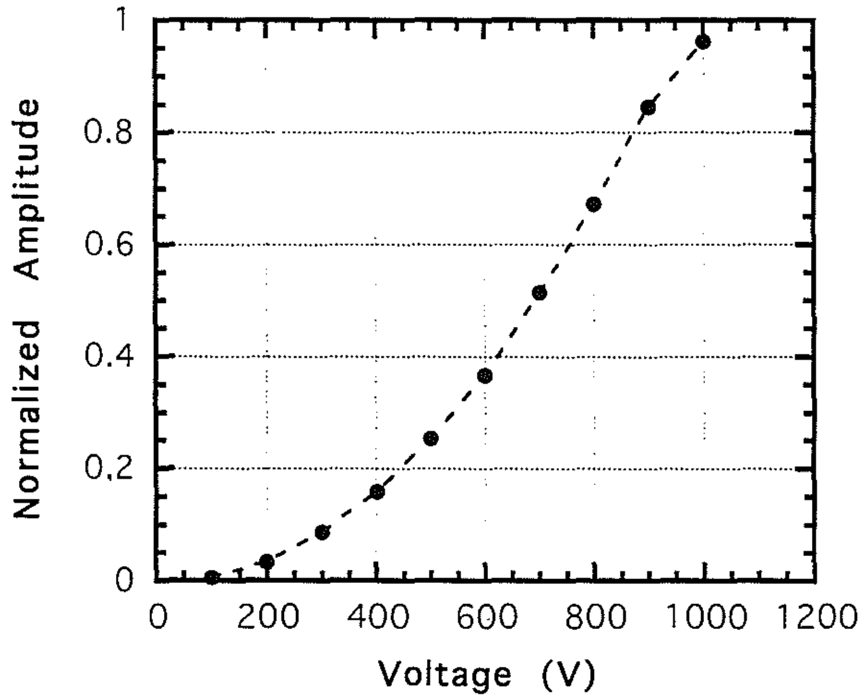


Figure 10: Relationship between the voltage of the exciting electric pulse and the amplitude of the electroseismic waveforms in the sandstone layered model.