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Stoneley wave induced electrokinetic potentials in large sandstone blocks

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1 Introduction

This paper describes the results of lab experiments in which electro kinetic potentials, i.e. streaming potentials, are stimulated in large sandstone blocks by an acoustic source. The objective of this study is to design a new logging system called EKL to estimate soil and rock permeability by measuring electro-kinetic signals. A compact experimental set up was planned to measure the electro-kinetic effects in two sandstone blocks of different permeabilities. Suitable laboratory samples, i.e. two sandstone blocks were obtained and saturated with water. Several acoustic sources were tested to find the most suitable technique to generate seismic induced electro-kinetic signals. An electric receiver was developed to measure the electric response signals from the rocks. At least the acoustic wave field was measured using two hydrophones, one as a reference the other moving with the electric receiver. Several tests in two sandstone blocks were run. This set up allowed to estimate the electro-kinetic coefficient, i.e. to normalise the electric field to the pressure, and to correlate it with the hydraulic permeability

2 Physical background of seismic-induced electro-kinetic effects in boreholes

Borehole Seismic Modes

A streaming potential is generated across a water-saturated porous rock when fluid flow is induced by an applied pressure gradient. The overwhelming majority of this work has been in the area of DC streaming potentials, while very little work has been done in the area of frequency-dependent streaming potentials. Although in laboratory studies a DC pressure signal can be easily established, it is an improper method to stimulate electro-kinetic signals in boreholes.

A number of logging methods are used as standard tools to detect and characterise permeable zones in the subsurface. Only seismic waves generated in boreholes are a dynamic method in which fluid flow is involved and therefore provides important information about permeability. The goal of this work were to make laboratory measurements of the electric fields induced by a borehole seismic wave and to study to which extent it can be used in the determination of formation permeability.

One of the most important acoustic modes, which is related to fluid motion in porous rocks, is the S*toneley wave*. It is a guided wave in the borehole that arrives after the shear wave and the fluid compressional wave. Another important mode is the so-called *slow compressional wave*. It is a body wave and travels in the fluid in the pores at a velocity less than that of the fluid. Its amplitude decays rapidly with distance, turning into heat before it can be detected by a sonic log. No pores, no fluid, no slow compressional wave.

Although predicted by Biot in 1956, the slow wave was not detected in the lab until 1982 by Johnson and Plona. Biot theory shows that acoustic waves create relative motion between the fluid and the solid frame due to inertial effects. As the matrix is accelerated, the fluid lags behind, resulting in viscous dissipation of acoustic energy. At low frequencies, the viscous skin depth is much larger than the pore size. Fluid and solid are virtually locked together moving in phase. At higher frequencies, the viscous skin depth is very small and the fluid and solid are essentially decoupled. Velocity is a maximum, and attenuation is low. For water-saturated rocks, the critical frequency in the Biot theory, where attenuation and dispersion are maximum, is often on the order of 100kHz. Increasing viscosity pushes the critical frequency even higher. Therefore seismic waves and sonic logging are almost always in the low-frequency range of the Biot theory. At low frequencies the Biot slow wave is diffusive and at high frequencies it is propagatory. The propagatory wave is very difficult to observe in rocks (Johnson and Plona, 1982). The diffusive mode of the slow wave is of practical importance for permeability estimation using borehole Stoneley waves.

The Stoneley wave is a guided mode propagating primarily in the borehole fluid and applying pressure against the borehole wall. This pressure generates a diffusive wave in the pore fluid in the rock. Energy conversion occurs from Stoneley wave to diffusive wave causing both attenuation and reduction of the Stoneley wave velocity. In practice, it is used to estimate the permeability of rock formation. The wave motion in the fluid-filled pores acts as a pump forcing fluid into pores and fractures. Higher permeability absorbs more energy, thus reducing the amplitude of the Stoneley wave.

Seismo-electric conversion

In Biot's theory a wave propagation is proposed in two-phase porous media that allows for the fluid phase to move relative to the solid phase during seismic wave passage. Energy dissipation is assumed to be solely due to the viscous shearing of the fluid. When a fluid electrolyte moves relative to a solid, an electric field is generated that migrates ions (**Figure 1**). The generated electric field pushes on the excess ions in a direction opposite to the applied pressure gradient. This electric field migrates ions in the fluid and thus dissipates energy as Joule heat. The potential associated with this electric field is called the streaming potential. In most cases the electro-kinetic losses can be ignored if the electrolyte molarity is in the order of 0.1 M or greater (Pride and Morgan, 1991). In this case wave propagation isn't influenced by electro-kinetic forces.

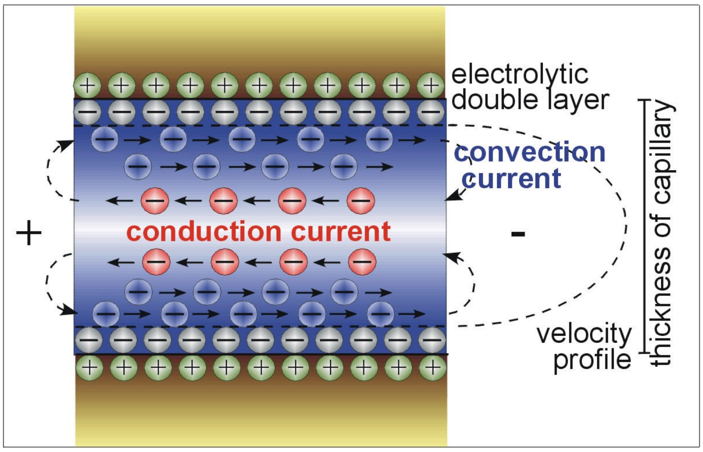

Figure 1: *Principle of generation of streaming potential*

As the fluid flows, it carries with it the mobile charges of the diffuse portion of the double layer producing an electrical convection current. As fluid flows into the entrance region of the capillary, the positively charged fluid of the diffuse double layer is replaced by neutral electrolyte. This effectively exposes the negative surface charge and results in the entrance having a net negative charge. Simultaneously at the exit, the positively charged double layer fluid is streamed out into the neutral electrolyte resulting in the exit region acquiring a net positive charge. An electric field is therefore induced along the length of the capillary. The potential associated with this field is called streaming potential.

In this case the observed streaming potential travels with the guided wave in the borehole. This is the *first type* of seismo-electric conversion. When this seismic wave encounters an interface in which there is a change in medium parameters as the porosity, permeability or the ion concentration of the pore fluid an electromagnetic wave is generated. This EM wave has the frequency of the seismic wave that generates it. It is the *second type* of seismo-electric conversion.

Pride (1994) derived a set of coupled equations that describe the conversion of energy between the electromagnetic and acoustic wave fields. These equations have the form of Maxwell's equations coupled to Biot's equations. The coupling between the seismic and electromagnetic wave fields lies in a frequency dependent coupling coefficient. This set of equations is the result of volume averaging the continuum equations applied to the grains and pore fluid.

For a horizontally layered medium Ranada Shaw (2005) showed, that a vertical propagating acoustic wave field can be expressed in terms of their lateral variation and then decoupled into two independent sets of partial differential equations. These two sets are the P-SV-TM and the SH-TE case. The P-SV-TM coupling includes the interactions between the compressional, vertical shear (SV) and the TM (traverse magnetic) electromagnetic wave, while the SH-TE coupling includes the interactions between the horizontal shear (SH) and the TE (traverse electric) electromagnetic waves. TM and TE refer to the polarisation of the magnetic and electric fields in the electromagnetic wave.

3 Petrophysical characterisation of the Bentheimer and Roman sandstone blocks

In the above section 2 the generation of streaming potential was described as a multi physics problem, in which the wanted permeability depends on several petrophysical parameters. Pride's paper describes a model for the coupling between the elasto-dynamic and electromagnetic wave fields. Many petrophysical parameters are involved in this coupling, which are listed below:

Table 1: *Parameters involved in the seismo-electric effect*

solid and fluid particle velocities
Porosity
the averaged bulk stress
fluid pressure
fluid, solid and bulk densities
fluid viscosity
dynamic permeability
Tortuosity
fluid and rock conductivity
electrical permittivity
zeta-potential

In order to extract the permeability from electro-kinetic logging it requires the knowledge of all these parameters. Therefore two sandstones of different origin, the Bentheimer and Roman sandstone block, were characterised in the laboratory to determine most of the petrophysical parameters of **Table 1**.

Core samples were obtained while drilling through the sandstone block and petrophysically characterised in the laboratory. The core measurements were carried out in the petrophysics lab of Geophysica GmbH (Stolberg).

A core logger from Geotek Ltd consisting of several devices provides the compressional wave velocity v_P and the bulk density ρ. The apparatus to measure the ***acoustic velocities*** consists of an ultrasonic transducer, which is energized by an electrical pulse. At the other end of the sample a transducer of the same type measures the travel time of the pulse, which is then converted into the appropriate acoustic velocity.

The interaction of γ-rays by Compton scattering is dependent only upon the number density of the scattering electrons. This in turn is directly proportional to the ***bulk density*** of the rock material. The device, to measure the density, consists of a detector and a source of gamma rays whose primary mode of interaction is Compton scattering. The attenuation of the γ-rays is exploited for the determination of the bulk density ρ.

The ***electrical resistivity*** (Ωm) (conductivity S/m) of the rock samples is estimated by applying a standard four-electrode array. Power is supplied to the current electrodes attached to both ends of the sample. The voltage difference is picked up by copper wires wound around the sample. In order to avoid polarisation effects a low frequency current of 8.33Hz is supplied. Depending on the conductivity of the sample the current strength varies between 100nA and 10mA. The measurements are carried out with fluids of different conductivity. Plotting the bulk conductivity against fluid conductivity provides the formation factor.

A Gas Pycnometer provides reliable measurements of ***rock matrix density***. This instrument is based on the principle of gas intrusion into pores. The device performs a fully-automated, non-destructive test. The Gas Pycnometer uses the ideal gas law to determine the volume of a sample, given a known volume of the sample chamber and gas reservoir and a change in pressure. An isolated chamber is floated with helium gas applying a pressure of 1.5-1.7 bar. The volume of the sample is then converted into the density if the weight of the sample is known. This instrument is also capable of measuring pore volume and pore volume distribution. The porosity is crosschecked by using an alternative way, i.e. the method of Archimedes.

Zeta potential measurements were made using a technique called micro-electrophoresis. A high quality stereoscopic microscope is used to comfortably observe colloidal particles inside a chamber called an ***electrophoresis cell***. Electrodes placed in each end of the chamber are connected to the Zeta Meter unit which creates an electric field across the chamber. Charged colloids move in the field and their velocity and direction are related to their zeta potential. These measurements were made with a device from the University of Bonn.

The ***hydraulic permeability*** was measured using a commercial apparatus. Applying a constant pressure gradient across the sample the volume flow of an inertial gas (nitrogen) is measured and converted into permeability by Darcy’s law.

The ***formation factor*** measurements were performed using an aqueous solution of sodium chloride as the pore solution because the conductivity of a few standard concentrations of this electrolyte are known to a high precision. A range of concentrations between 0.01 and 1mol were used. The specimens were first vacuum saturated with one of the NaCl electrolyte concentrations and then mounted.

Formation factor, F, is defined as

$$F = \frac{R_0}{R_w}$$

where R_0 is the resistivity of a formation fully saturated with water of resistivity R_w. It is related to formation porosity φ via a number of empirical relationships of the form

$$F = \frac{a}{\varphi^m}$$

where m is the cementation exponent and a is sometimes called the Archie constant. **Figures 2 and 3** display the results of the conductivity of the fluid saturated rock samples versus the conductivity of the saturating fluid.

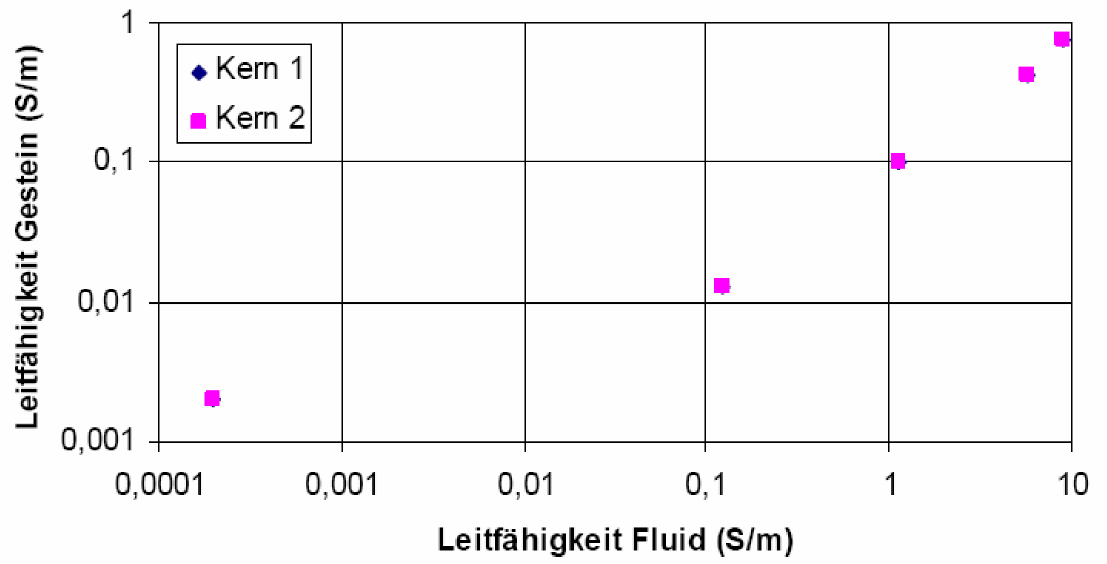

Figure 2: Bentheimer sandstone block: *Electrical conductivity of the fluid-saturated sample versus fluid conductivity*

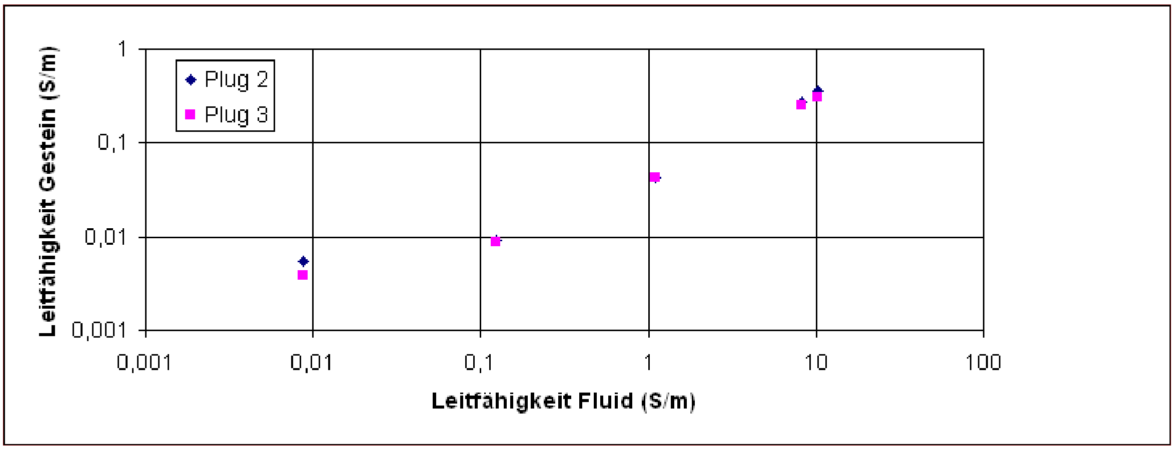

Figure 3: Roman sandstone block: *Electrical conductivity of the fluid-saturated sample versus fluid conductivity*

Rock samples from the two sandstone blocks were petrophysically characterised in the lab, which yielded following results (**Table 2**):

Table 2: *Physical properties of two sandstone blocks*

Physical properties	**Bentheimer**	**Roman**
Weight/Height/Diameter	1.5 tons / 1.1m / 0.7m	2.5tons / 1.8m / 0.7m
Hydraulic permeability k_o (mDarcy)	2250	6.25 parallel 2.33 perpendicular
Porosity Φ (p.u.)	25	15
P-wave velocity (m/s)	2100 (dry) 2550(saturated)	3300 parallel 3400 perpendicular
ζ-Potential (mV) *@ 30mS/m of aqu. solut.*	22	19
Formation Factor F	1st sample: 11.9 2nd sample: 11.8	1st sample: 28.33 2nd sample: 30.9
Density (kg/m3)	2000 (dry) 2250 (saturated)	2200 (dry) 2360 (saturated)

4 Electro-kinetic responses obtained from sandstone blocks

Electro-kinetic (EK) measurements were carried out in large sandstone blocks (**Figure 4**). A simple electrode dipole and hydrophones shown in **Figure 5a** were used to sense the electric field variations and the acoustic field, respectively (**Figure 5b**). The source was a short hollow steel tube held near the top of the borehole and hit on top with a hammer.

Figure 4: *Roman sandstone (left) and Bentheimer sandstone (right). One (left) was wrapped round in a plastic foil, the other (right) was put in a container. Both were saturate with fresh water.*

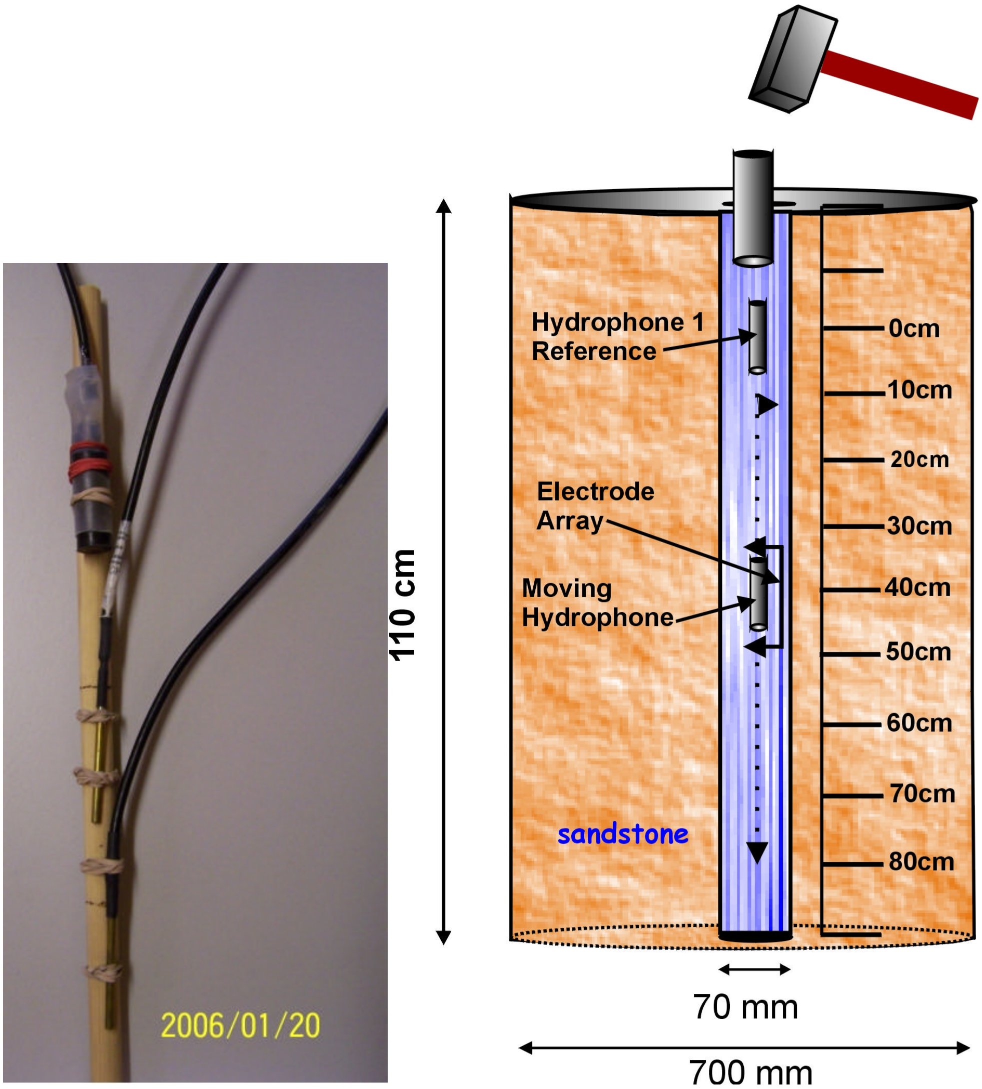

Figure 5a,b: *Experimental setup*

I first verified that the signals are originated in the sandstone by observing no signals when the borehole was screened with a metal or plastic tube. I also run a null test in a water filled container without a sandstone. Likewise no electric signals were observed which implies that the signals observed in the sandstone blocks are a result of electro-kinesis.

Figure 6 shows the waveforms from the Bentheimer, in which can be seen a low frequency pressure wave travelling down the block with a speed of 600m/s. This velocity is consistent with that of the Stoneley wave in these conditions, even though the sensors are at distances that are a fraction of a wavelength from the source. The high frequency signal travelling with this wave is caused by the source ringing with a period that can be related to the length of the metal tube. The EK waveform shows a signal travelling at the same velocity as the pressure wave. The average ***normalised electro-kinetic factor*** (NEF) is calculated as 2.49μV/Pa-m with a spread of +/- 0.74μV/Pa-m between levels. Surprisingly, there are no reliable signs of the electromagnetic waves, also called initial burst. It may have been cancelled out across the dipole.

Using a finite element code (Pain et al., 2005) the response of the block was modelled using the measured water conductivity of 0.07S/m and the zeta potential given in **Table 2**. Source signature and magnitude are defined by the response at the upper hydrophone. The other fluid and matrix properties were calculated from the measured P-wave velocity, V_p, an estimated V_p/V_s ratio and from standard values for water and sandstone. A typical pair of waveforms from the model has been superimposed on the measured waveforms in **Figure 7**. The average model NEF is 2.01μV/Pa-m.

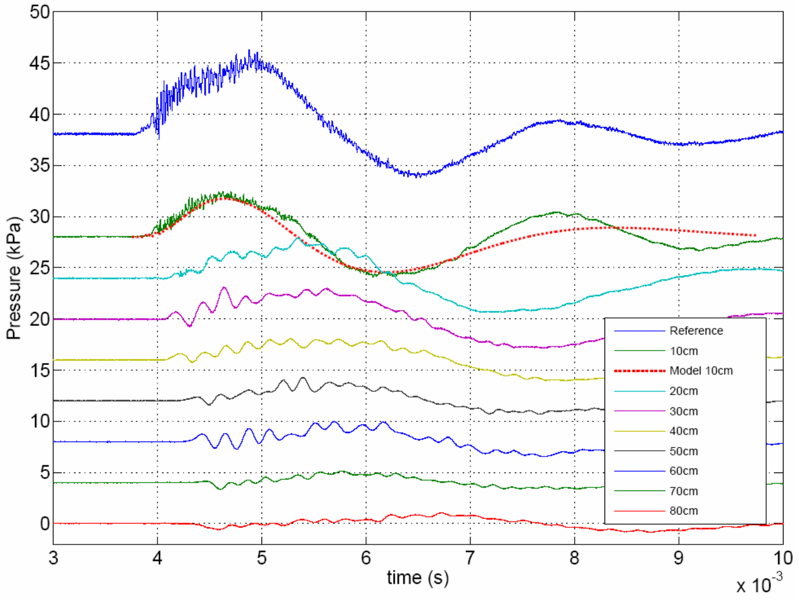

***Figure 6:** Pressure at the moving hydrophone at different positions in the Bentheimer sandstone. A low frequency and a high frequency wave can be seen. Superimposed are results from the model at 20cm.*

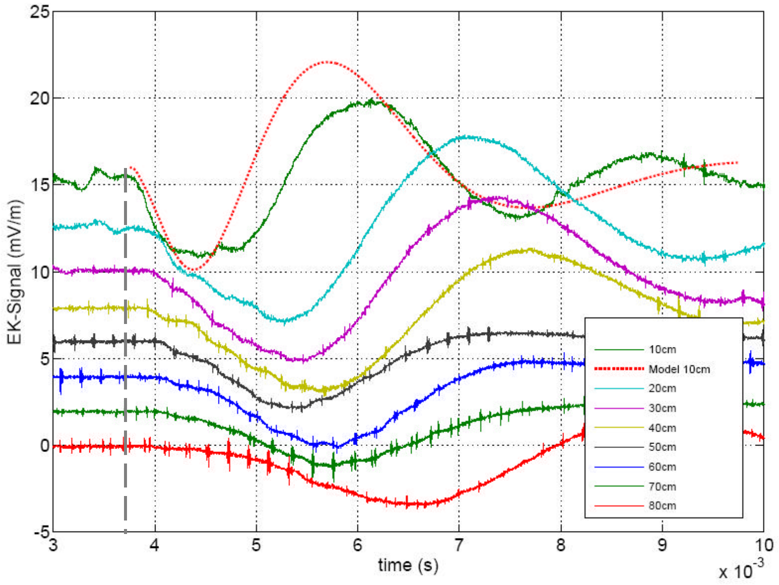

***Figure 7**: EK signal at the moving electric dipole at different positions in the Bentheimer sandstone. The vertical lines indicate the time at which pressure passes the reference hydrophone.*

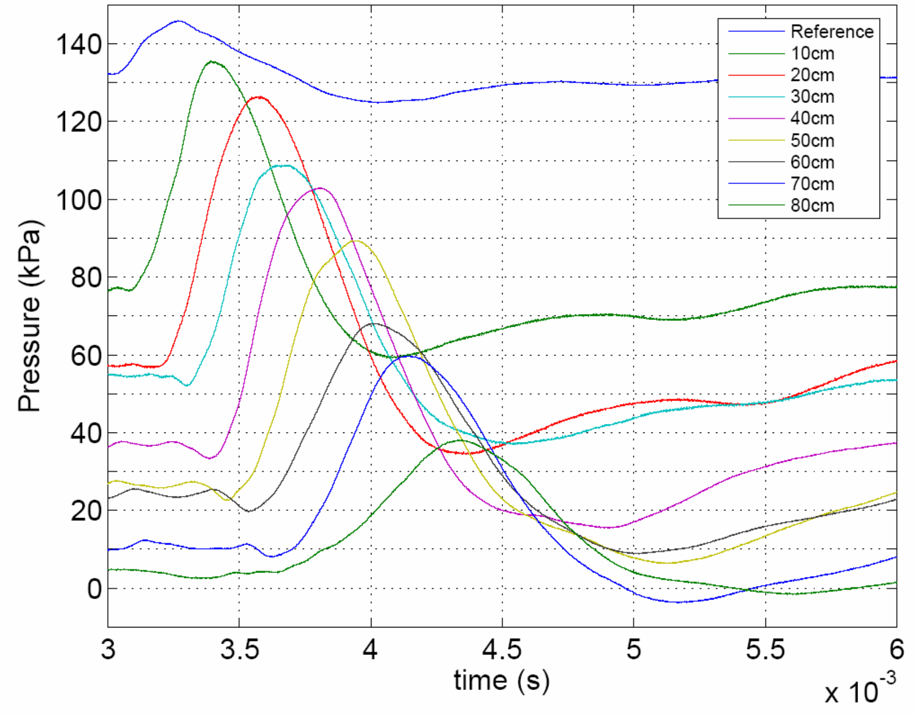

***Figure 8**: Pressure at the moving hydrophoneat different positions in the Roman sandstone. A single wave at about 700Hz is observed.*

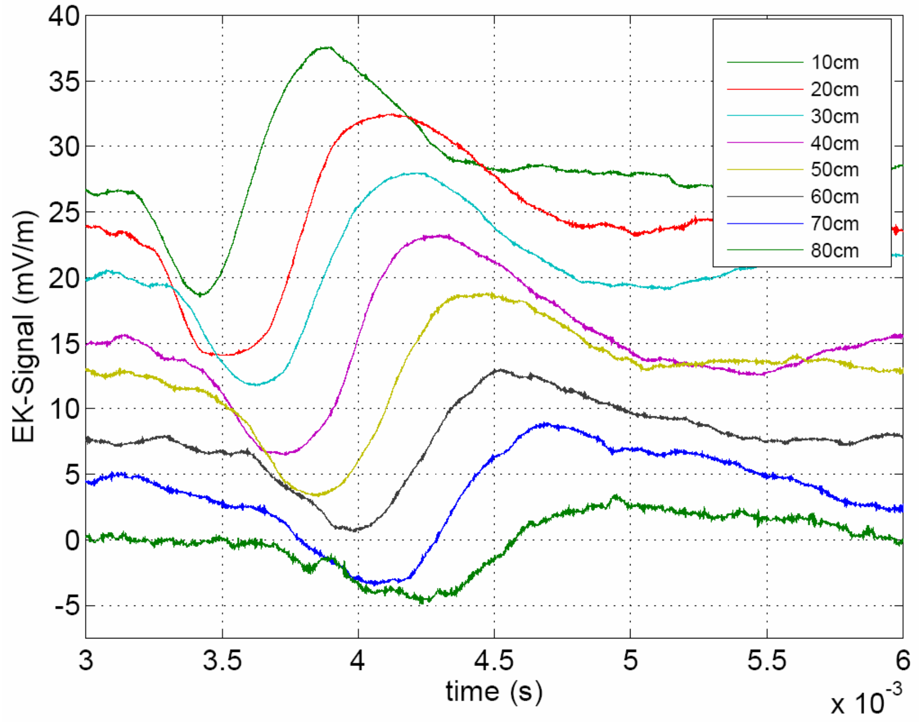

***Figure 9**: EK signal at different positions in the Roman sandstone.*

Similar measurements were made in the Roman block, giving an average NEF of 0.16 +/- 0.02µV/Pa-m (**Figures 8, 9**). The results of all measured and modelled values are summarized in **Table 3**. The overall agreement shows that the model is able to predict the response of actual EK measurements with reasonable accuracy. The results also demonstrate experimentally that NEF is a function of permeability. While not conclusive, it is unlikely that the large difference in NEF could be explained by the moderate difference in porosity between the two blocks.

Table 3: *Summary of the measured and modeled results obtained in the two sandstone blocks.*

		Bentheimer	**Roman**
ϕ	p.u.	24	15
K	mD	2200	6.25
ζ	mV @ 0.03S/m	21.4	19
NEF Measured	☐V/ Pa-m	2.49 +/-0.74	0.16 +/- 0.02
NEF Modeled	☐V/ Pa-m	2.01	0.5

According to Biot's theory porosity and permeability of rock formations can be derived from borehole electro-seismic measurements. Specifically, the porosity can be derived from the NEF and the permeability can be derived from the NEF versus the frequency of Stoneley wave induced electrical field. However, several petrophysical parameters must be known to estimate the porosity and permeability. Many of them, which are involved, are not directly accessible in situ such as tortuosity or zeta-potential. Both, porosity and permeability, are a linear function of these parameters. **Figure 10** displays a possible transform between NEF and permeability obtained from Lab observations (red) and from finite element modelling (blue) as well. Due to different input parameters both transforms are separated. The last one was used to estimate the permeability in limestones.

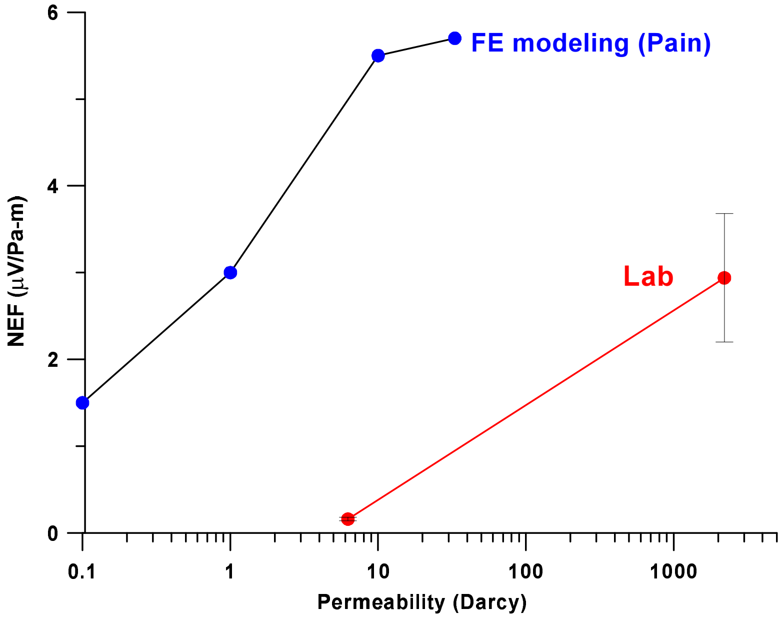

Figure 10: *NEF vs. hydraulic permeability obtained from the Bentheimer and Roman sandstone block (red), and as used in the borehole experiment (blue*

5 Summary

Laboratory results from two sandstone blocks confirm experimentally that EK signals vary with permeability and that Stoneley induced electrical fields can be generated by a simple acoustic source. Results agree qualitatively with those predicted by the model and support the conclusion that NEF depends on permeability. The laboratory investigations suggest that the determination of the NEF has the potential to measure formation permeability.

Acknowledgements

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