Borehole electrokinetic responses in fracture dominated hydraulically conductive zones

Craig W. Hunt and M. H. Worthington

T. H. Huxley School of Environment, Earth Sciences and Engineering, Imperial College of Science, Technology and Medicine, UK

Abstract. Electrokinetic borehole logging experiments conducted in fracture dominated Devonian metasediments and Carboniferous limestone boreholes containing dissolution discontinuities, indicate a strong relative amplitude correlation between a downhole electrokinetic response and previously obtained hydrogeological data for the respective boreholes. Voltages in the range 0.2-1.5 volt were recorded per MPa of gauge pressure induced in the borehole fluid. A relationship between fracture aperture and the frequency content of the electrical data has also been observed.

Introduction

Electrokinetic (EK) phenomena have been the subject of a considerable body of publications over the last 50 years. Variably referred to as the electrokinetic, electroseismic or seismelectric effect of the second kind [Ivanov, 1939], electrokinetics is the process whereby the deformation of a saturated porous elastic medium can generate an electrical potential, normally referred to as the streaming potential [Fitterman, 1978]. Recent publications that have developed the theory of electrokinetic effects in fluid saturated media include Fitterman [1978], Neev and Yeatts [1989], Pride [1994], Pride and Haartsen [1996] and Haartsen et al. [1998]. Electrokinetic signals from buried interfaces have been recorded with seismic sources and electrode receivers deployed on the surface [Thompson and Gist, 1993; Butler et al., 1996; Mikhailov et al., 1997a]. However, very limited depths of penetration were achieved due to the exponential decay of the electric field in a conducting medium. This prompted Mikhailov et al. [1997b] and Zhu and Toksoz [1998] to perform experiments with a surface seismic source and downhole electrodes. Our approach is to use a moveable downhole seismic source and downhole electrodes with a fixed source/receiver spacing. The three boreholes we have chosen to study are all from sites where previous extensive hydrogeological experiments have been carried out. So we are able to compare our electrical signals, which we believe to be electrokinetic in origin, with other hydrological and geophysical data.

Method

We attempt to maximise the borehole fluid displacement in the direct vicinity of discontinuities that intersect the borehole. The source consists of a 75cm steel tube through which runs a steel shaft attached to a cylindrical nylon block. The shaft can slide freely through the steel tube and is operated by means of a pull rope at the surface(Figure 1). The pressure pulse is generated by the nylon block which displaces water as it moves upwards to strike the body of the tool. The pressure pulse is enhanced because this rapid motion occurs within the confines of a hole which is only slightly wider than the diameter of the tool. We chose this very simple but effective arrangement partly because we were at pains to avoid any spurious electrical signals that might have arisen from some more sophisticated electromechanical mechanism. A single hydrophone is positioned 2.5 metres below the source and at the mid point of a 1 metre electrode dipole. The positive and negative electrodes are composed of steel mesh and are connected to the surface via shielded cable. All electrode records shown below are normalised with respect to the peak pressure recorded on the hydrophone. The hydrophone has been calibrated in the laboratory to obtain a direct conversion from hydrophone voltage output to gauge pressure. The electrode data are plotted at a depth corresponding to the mid point of the electrode dipole.

Results

Borehole A: Reskajeage test site

The Reskajeage quarry test site in Cornwall (UK) was developed for studies into the nature of fluid flow in a fracture dominated hydrogeological environment. A series of unlined boreholes were drilled into the Mylors slates, a marine metasediments unit of Devonian age. Discontinuities abound in the subsurface environment and detailed core studies have shown that they occur as angled fracture sets as well as bed planar jointing. There is effectively no matrix permeability and groundwater flow is fracture dominated.

Figure 2 shows our electrode data compared with packer test results. Signals of up to 4 millivolts were obtained from one source impulse. Mains harmonic noise has been removed from these data using a method described by [Butler and Russell, 1993]. A 100 ms pre-trigger was used in the recording system. The depth interval between the packers was 5 cm and the sample interval was between 5 and 10 cm. The peak electrode amplitude curve appears to be approximately a smoothed version of the packer data. We would expect a one metre electrode dipole to produce less well resolved data than these exceptionally detailed packer results. Where the correlation is poor, particularly between 10 and 11 metres depth, it is entirely possible that the electrokinetic survey is only providing information about the rock volume directly around the borehole, whereas a packer test will explore deeper into the fracture network.
Borehole B: Reskajeage test site

Borehole B is located some 50 m from borehole A within the Reskajeage site. Additional data from this hole includes a 5 m interval packer test and a self-potential (SP) log which was acquired by A. Binley (University of Lancaster, UK). Self potential is particularly relevant to the investigation of electrokinetic methods since it is associated with the disturbance of the dielectric layer [Corwin and Hoover, 1979; Ogilvy et al., 1969]. Ogilvy et al. [1969] highlight the similarity between an SP response as a result of fracture leakage on a reservoir floor and the corresponding electrokinetic response in the same region. Figure 3 demonstrates that this relationship holds true for our locally induced electrokinetic responses.

Borehole C: Middlebarrow Limestone site

Figure 4 shows the data gathered at our borehole C at Middlebarrow limestone quarry site, South Cumbria, UK. Groundwater flow is entirely dominated by quarry wide dissolution features. At around 22 m all available data indicate an abrupt change with the resistivity values rapidly decreasing and the electrokinetic response rising sharply. This is supported by the CCTV observation data which indicate that at this point we are entering a zone of cavity features. The most substantial of these is described as being a zone of complex fractures between 2-5 cm in aperture [Brown and Slater, 1999]. The CCTV data are represented as lines on the top of figure 4b. These lines vary in thickness according to fracture density, and length according to maximum estimated fracture aperture. The substantial peak in the electrode response in figure 4b is clearly associated with this highest fracture density in addition to the widest apertures. This is an exceptionally electrically quiet site and the data in figure 4 are plotted as recorded with no filtering applied.

Note also that the signals in figure 4a begin before time zero. Time zero is at 100 msecs due to the pre-trigger setting and is defined as the moment the blocks impact. However, fluid pressure will build up within the immediate vicinity of the source from the moment that the nylon block starts moving within a confined space, which we estimate to occur approximately 50-100 ms before impact.

Figure 1. Downhole tool. (A) Steel tube, (B) nylon block, (C) pull rope, (D) supporting cable, (E) rock, (F) crack, (G) steel mesh electrode, (H) hydrophone.

Figure 2. Data from borehole A. (A) Electrode response data. + and - symbols indicate polarity of the signal as recorded. (B) Peak electrode voltage responses normalised for applied seismic pressure. Dashed line is estimated system noise level. (C) Packer test data. Values expressed as mm below graph C are aperture width ranges gained from impression packer data.
Discussion

Explanations are required for certain key features of the data, which will not be forthcoming until we have completed extensive analytical and numerical modeling and further fieldwork. However, we can suggest some most likely causes of what we observe.

The electrode signals near time zero are always predominantly one sided. This contrasts with the hydrophone records which are always two sided. In addition, the hydrophone detects tube waves of approximately half the amplitude of the first arrival that propagate down and up the holes after reflecting from the free surface or obstructions below. However, negligibly small electrode signals are associated with these tube waves. The maximum electrical signal occurs when the electrode is opposite the cracks and the source is 2.5 metres above. So the fluid flow in the cracks, which would result in an electrokinetic signal, is more likely to be predominantly caused by a seismic wave in the rock that distorts crack aperture as it passes, rather than by the source directly forcing fluid into cracks. Since this occurs within the near field region of the source, one cannot speak specifically of P waves or S waves and a DC component in the waveform can be expected.

The polarity of the electrical signal changes in figure 2 at approximately 12 and 16 metres depth. We can expect a charge separation due to fluid flow over the characteristic length of the crack. Depending on the fracture diffusivity, this length could be on the order of tens of cm. A vertical electric field in the borehole would then result from a crack at some angle to the horizontal. It is not difficult to imagine some complex and realistic network of cracks that produces a resultant vertical electric field of either sign.

Another possible explanation comes from the work of Bogoslovsky and Ogilvy [1972] who have performed laboratory experiments to study streaming potential in fissured media and report changes of sign of the potential as a function of clay content. Unfortunately, at present our field experiments are not sufficiently well constrained to enable us to relate our data either to the details of crack geometry or clay content.

Comparison of Reskajeage and Middlebarrow data

Substantially larger relative electrode responses for the same applied pressure are recorded at Middlebarrow compared to Reskajeage; up to 400 mV/MPa in boreholes A and B and up to 1500 mV/MPa in borehole C. Fitterman [1978] quotes values for streaming potential in the range 10 to 700 mV/MPa.

There is also a substantial difference in the response characteristics of the two sites. The two Reskajeage electrode data both have relatively short responses (5 - 35ms). The signal from Middlebarrow spans in excess of 200 ms and has a lower frequency characteristic than the Reskajeage data.
Conclusions

We show strong correlations between electrical signals and the location of open fractures and we believe we are causing water to flow in and out of these fractures. An electrokinetic mechanism is consistent with these observations and with the observed correlation with self potential in borehole B.

We note that there is a difference in frequency content between our Reskajeage data and Middlebarrow data and tentatively relate this to the aperture of the fissures at the two sites (1-5 mm at Reskajeage and up to 5 cm at Middlebarrow). However, the main aim of this paper is to present raw field data which others might wish to reproduce. The development of the required theory and numerical modelling is our current work in progress.

Acknowledgments. This research was funded by the Natural Environment Research Council (NERC) within the realising our potential (ROPA) programme. CWH was supported throughout this study by a NERC research training award. Assistance with the calibration of the hydrophone by Schlumberger Cambridge Research Ltd and in particular Dr Mike Barrett is gratefully acknowledged. Assistance from Mr B. Watkins (Manager, Reskajeage site) and Dr A. Binley (University of Lancaster, UK) is also gratefully acknowledged.

References


C.W. Hunt and M.H. Worthington, T.H. Huxley School of Environment, Earth Sciences and Engineering, Imperial College of Science, Technology and Medicine, Prince Consort Road, London, SW7 2BP, UK.

(Received October 11, 1999; revised February 14, 2000; accepted March 7, 2000.)