Borehole electrokinetics

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We now understand the electrical double layer that exists between the minerals that form the rock matrix and the bulk electrolyte which saturates the pores of the rock, at least in the steady state. It is the presence of this double layer that allows the link between the electrical properties and the fluid-flow properties of the rock to exist. In addition, because pore fluid pressure perturbations can be caused by the passage of poroelastic waves, there is also a link between the seismic properties of rocks and their electrical properties. Although postulated more than 70 years ago, there has

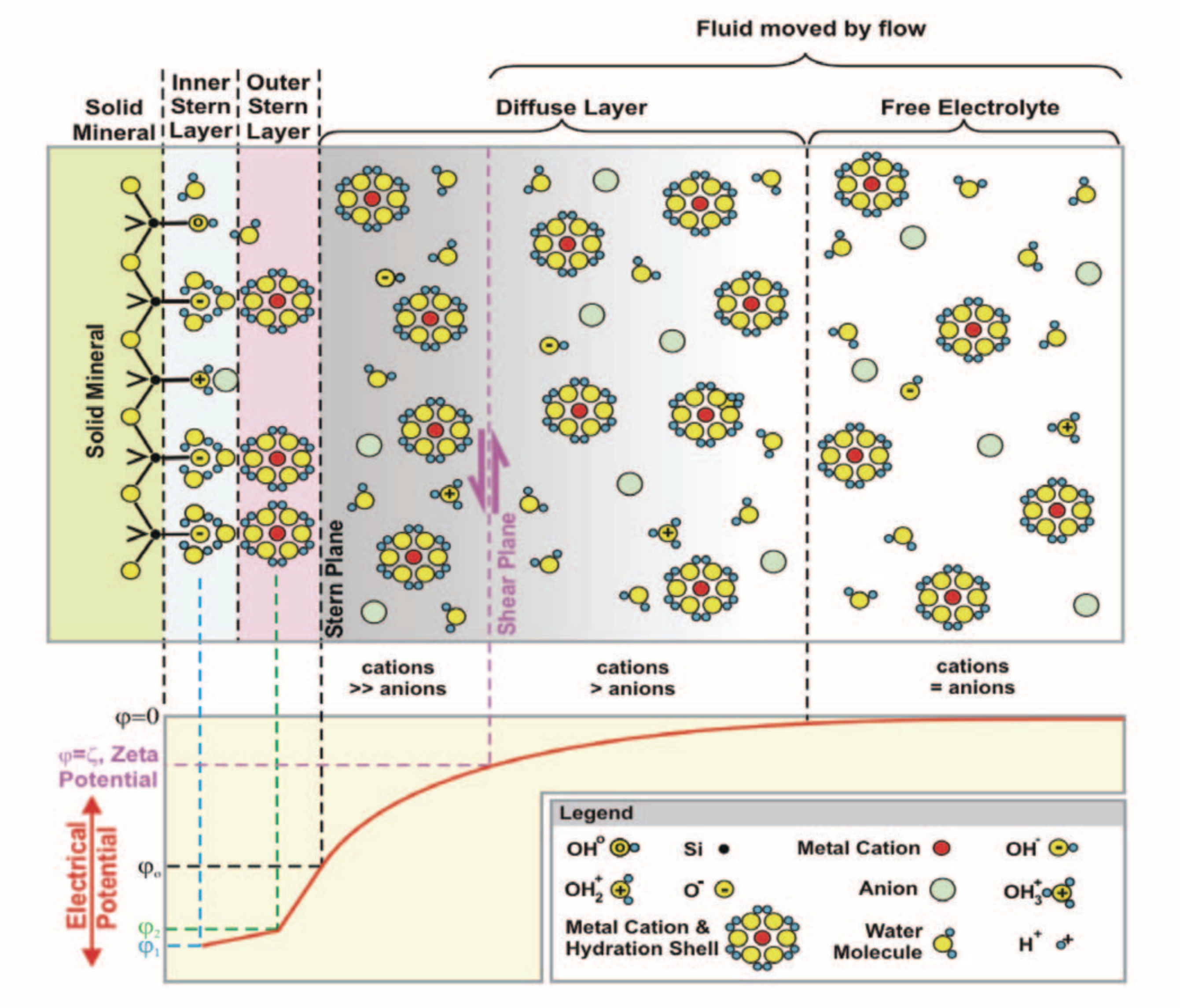

Figure 1. *A schematic representation of the electrical double layer that exists at the interface between a rock matrix and the pore water. The rock is shown on the left in green. Here it is silica, which forms three types of surface sites (positive* $SiOH_2^+$*, neutral SiOH and negative* SiO^-*). The relative concentrations of these depend upon the fluid pH. At reservoir fluid pHs, the negative sites dominate. Hydrated positive ions (in red) are adsorbed to these sites. The adsorbed positive ions cannot cancel out all of the negative surface charge, so there exists a fluid diffuse layer which has an excess positive charge (more hydrated cations than anions), which falls off exponentially until there are equal numbers of positive and negative ions (the bulk fluid). The thickness of the diffuse layer depends upon fluid concentration. At low concentrations it may be several microns thick, which is sufficient to ensure that a rock with small pores has all of its aqueous fluid in the form of the diffuse layer rather than as bulk fluid. In this case there is no bulk fluid conduction, only surface conduction mediated through the EDL. Movement of fluid through the rock moves the bulk fluid (net electrically neutral) and that portion of the diffuse layer that is farther from the surface than the so-called shear plane (net electrically positive). Thus the fluid flow separates charge which creates the streaming potential, and ultimately a streaming counter-current.*

been an acceleration in the application of electrokinetic and seismoelectric principles to reservoir problems in general and to borehole measurements in particular. In this paper we review briefly the origin of electrokinetic and seismoelectric phenomena before looking at some of the new borehole applications that are being developed.

Introduction

Often the best understanding of the subsurface comes when we compare data from diverse sources or measurements of different physical properties. Occasionally, apparently independent physical properties are in fact coupled by a physical mechanism. When that happens, it is possible for us to not only predict one property from the other, but to also confirm our understanding of one with measurements from the other and vice versa. Electrokinetic and seismoelectric phenomena are examples of coupled properties that link the passage of poroelastic waves, fluid flow, and electrical flow in reservoir rocks. These phenomena occur over a wide range of spatial and time scales in all porous media that contain fluids. Because seismic data, pore fluid permeability, and hydrocarbon saturation are commonly used in the characterization of reservoir rocks, any relationship between them would be useful, whether the relationship is applied in downhole measurements, laboratory determinations, large-scale field measurements, or reservoir modeling.

The basic electrokinetic measurement is the streaming potential, which is the electrical potential that develops when an aqueous fluid flows through a rock. It is generally considered that the first person to measure a streaming potential was Georg Hermann Quincke in about 1859, which was followed some 20 years later in 1879 by Helmholtz's mathematical expression for the effect. In the following years, the phenomenon was studied by a number of researchers, including Clark (1877), Saxen (1892), and Bikerman (1932).

The origin of the phenomenon is the electrical double layer (EDL) that develops at the rock-water interface. Although thin, a few nanometers to a few micrometers depending on the fluid concentration, it is the EDL that mediates surface conduction in rocks, and it is shearing of the electrically charged diffuse part of the EDL that produces the electrokinetic effect (Figure 1).

Electrokinetic phenomena

In the case of electrokinetic phenomena, a fluid flowing through a reservoir rock moves ions in such a way that an electrical potential difference called the streaming potential is created, and an electrical current flows to restore the balance (the streaming current). The reverse process can also occur, and this is called electro-osmosis. If one knows the physics behind the coupling, one might in principle calculate the permeability of a rock from an electrical measurement without recourse to empirical data-fitting (Glover et al., 2006). What is more, because electrical parameters may be measured remotely by self-potential, telluric, magnetotelluric and GPR techniques, these data may in future developments be inverted to give regional or local fluid flow in a reservoir or other permeable system, or even the redox conditions inside the contaminant plume in a groundwater system. Already self-potential measurements have been used to map the convective flow of fluids around volcanoes using electrokinetic coupling. Maybe the same approach can be used to monitor the depletion of a water-driven reservoir in geothermal reservoirs or the sudden flow of water into a previously dormant but potentially seismically active fault prior to an earthquake. Applications are not necessarily restricted to measurement and monitoring. There have been studies, for example, involving the electrokinetic remediation of contaminated soil where the pollutant is ionic or water-soluble. Many of these applications have direct and useful applications in the hydrocarbon industry, and some are applicable downhole. For the purposes of this paper we will discuss one example of the application of electrokinetics in more detail: A group of researchers led by one of us at Imperial College London has been studying the remote measurement of streaming potentials along boreholes in order to detect the encroachment of water at production wells.

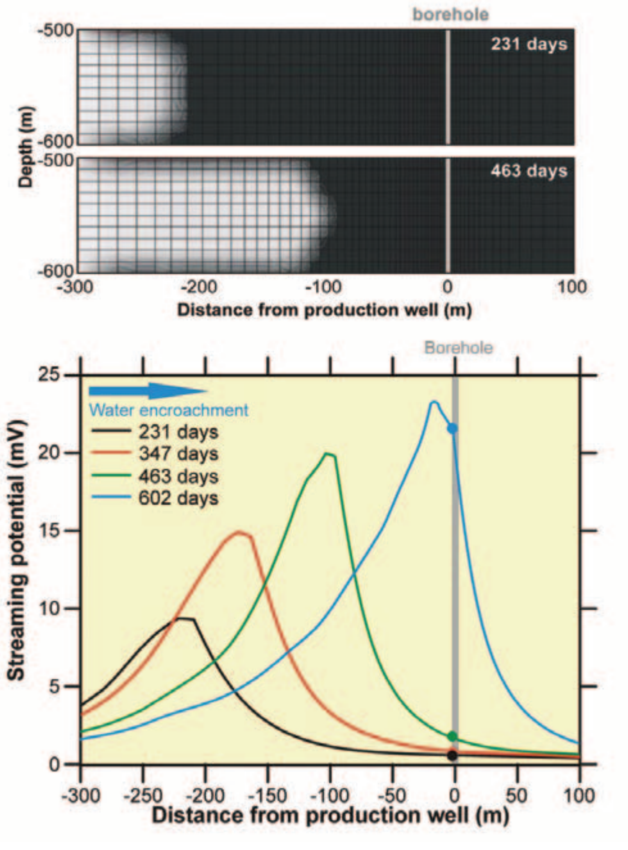

Figure 2. *Streaming potential versus distance from a production well along a 1D horizontal section through the center of the model, at four different time steps during a simulation with salinity* C_f *= 0.6 mol/L (seawater salinity). The peak of the potential curve is at the position of the advancing waterfront, but the envelope of the curve encompasses the production well when the front is several tens to hundreds of meters away. This is why streaming-potential measurements can detect advancing water fronts when they are still some distance from the well. (After Saunders et al., 2008).*

Downhole monitoring of potential water encroachment

Downhole monitoring of streaming potential, using electrodes permanently mounted on the outside of insulated casing, is a promising new technology for monitoring water encroachment toward an intelligent well. Recently a group of researchers at Imperial College London have used 3D finite-element modeling that combines both multiphase flow and electrokinetic components to investigate the behavior of electrokinetic streaming potential during oil production in a range of reservoir environments. They discovered that streaming potential signals originate at fluid fronts and at geologic boundaries where fluid saturation changes. When water encroaches on an oil production well, these streaming potentials can be measured at the borehole even when the front is 100 m away (Figure 2).

In the upper part of Figure 2, water flows toward a borehole. Two time points are shown. The bottom shows a graph of the streaming potential resulting from the movement of the fluid front. The maximum streaming potential occurs at the flood front. However, there are significant and measureable values of streaming potential generated ahead of the fluid front as well as behind it. The length scale over which the electrical signal decays with distance from the front depends upon the conductivity of the reservoir and confining layers; so the curve is steeper ahead of the water front (toward the production well) where the water saturation and electrical conductivity is low, and less steep behind the front where the electrical conductivity is higher. The length scale is not dependent on the streaming-potential coupling coefficient because this is zero ahead of the water front.

The value of the streaming potential measured at point P on the borehole wall is shown by the colored circles in the figure. This value increases as the water front approaches the borehole, reaching a maximum when the water breaks through. Thus, if we install streaming potential sensors on a production well and those sensors show an increase in streaming potential, we will know that water is approaching. If we want to know how far away the water front is so that the well may be shut off in time, we would need to be able to calculate the shape, and especially the maximum value of the curves given in Figure 2, as a function of the properties of the reservoir. Most of these properties are fairly well known and commonly used in reservoir models. The parameter with the biggest uncertainty is the streaming potential coupling coefficient of the rock-fluid combination. This is a key petrophysical property which dictates the magnitude of the streaming potential for a given fluid potential.

Currently, there is little high-quality experimental data that we can use to constrain the streaming potential coupling coefficient in reservoir rocks. Previous experimental studies have obtained data for sandstone cores saturated with relatively low-salinity brine (less than seawater). Formation water and injected brine in hydrocarbon reservoirs are typically more saline than this. Extrapolating data obtained at low salinity into the high-salinity domain suggests the coupling coefficient falls to zero at approximately seawater salinity, implying that streaming potential signals will be small in most hydrocarbon reservoirs. However, recent high-quality measurements suggest that measured signals should be resolvable above background noise in most hydrocarbon reservoirs, and that water encroaching on a well could be monitored while it is several tens to hundreds of meters away, even at very high salinities. This finding is in agreement with the new theoretical predictions being developed by the authors.

Another question mark hangs over the value of the streaming potential coupling coefficient as a function of water saturation. Recent measurements by a research group at EOST, Strasbourg, have shown that the streaming potential does not decrease as the water saturation decreases as was previously thought. Rather it increases as the water saturation drops from 100% to about 80% before decreasing to a value less than that at 100% saturation. While the reason for this is not at present clear, it may be associated with a double layer that develops at the interface between the water phase and the nonwetting phase when the nonwetting phase is present in sufficiently small fractions that it can be considered to be mobile. This hypothesis is to some extent supported by the recent theoretical findings of Etienne Lac of Schlumberger-Doll research center and J.D. Sherwood of Cambridge University. The peak in the streaming potential coupling coefficient is important for downhole electrokinetic applications because it amplifies the streaming potential due to the passage of a water front and makes the water encroachment signal easier to measure.

Seismoelectric phenomena

In 1933, Debye suggested sound waves could generate electric fields if they propagated through an electrolytic solution having a suspension of charged particles. This idea led to electrokinetic potential measurements at ultrasound frequencies that now form an industry standard technique for the characterization of emulsions and colloids. The proposal that the link between seismic and electric fields might be used as an exploration tool came as early as 1936 (an article by Thompson in the first issue of GEOPHYSICS), followed by the first field experiments in 1939 by Ivanov on the electric field generated by explosions. Ivanov was also one of the first to suggest that electrical phenomena occurring during earthquakes could be associated with electrokinetic phenomena. Beamish and Peart list "intermittent" research papers on observational field studies of electrokinetic phenomena between Ivanov (1939)and 1993 when Thompson and Gist published an important study related to the hydrocarbon exploration industry, and from which most modern studies stem.

Although we have chosen to use the term seismoelectric for this type of coupling, it should not be forgotten that the link is mediated by fluid flow. The passage of a poroelastic wave implies local perturbation of the pore fluid pressure and consequent quasi-contemporaneous fluid flow. It is the fluid flow that separates electrical charges in the diffuse layer and causes the electrical signal. Hence the seismoelectric phenomenon contains the electrokinetic process within it.

There are two different types of seismoelectric signal that are generated by poroelastic waves. The first is called coseismic because it is local to the seismic wave and arises from

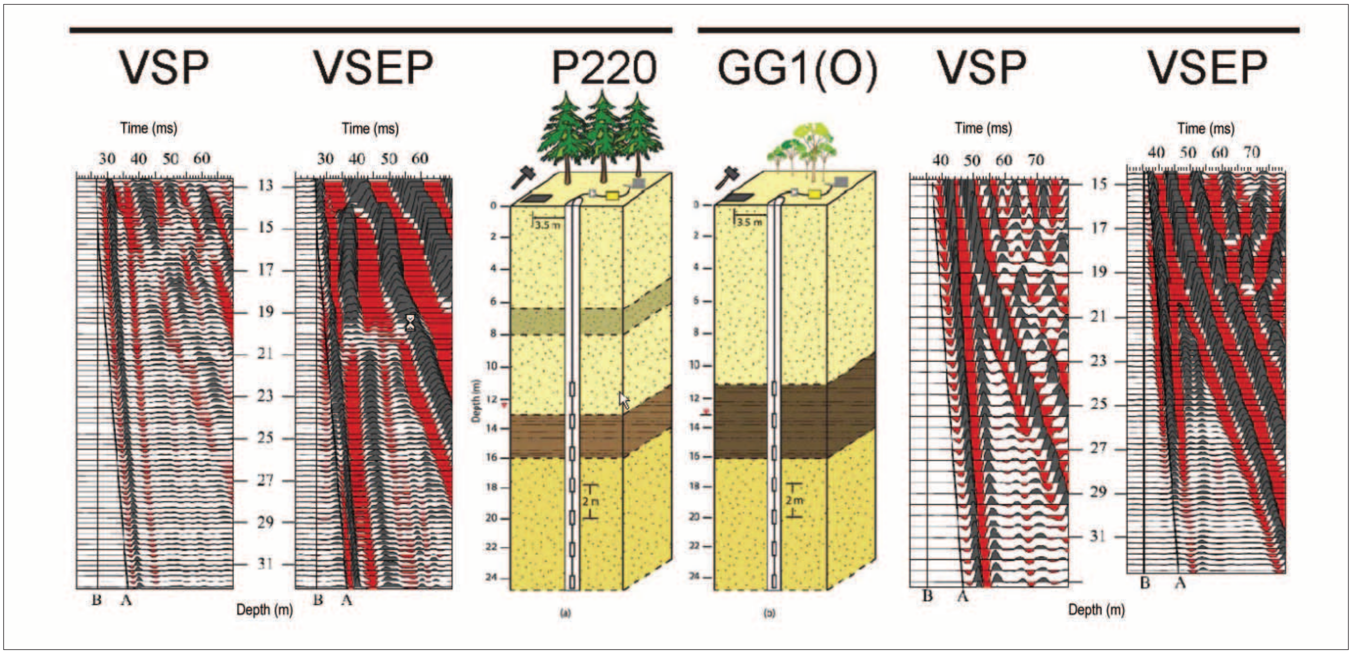

Figure 3. *Results from VSP and VSEP experiments in two boreholes (P220, water table 12.65 m; GG1(O), water table 13 m). The central two sketches show the arrangement of borehole P220 (left) and GG1(O) (right). The seismic source was a sledgehammer 3.5 m from the borehole collar. There were seven electrodes made from tinned copper wire wrapped around segments of PVC pipe (each 10 cm long and 2.5 cm diameter) spaced at 2-m intervals to make six dipoles. The signals were electrically buffered with a 10-fold gain and digitized at 24 bits with a sample rate of 62.5 us. The electrode array was raised in 25-cm increments with 20 sledgehammer blows for each, giving a maximum fold of 120 at each depth. The VSP and VSEP for borehole P220 are shown to the left of its sketch; the VSP and VSEP for borehole GG1(O) are shown to the right of its sketch. (Figure modified from those in Dupuis et al. (2009).)*

charge separation due to the local fluid flow (i.e., compression and dilatation created by the passage of a compressional wave). The cosesimic signal is always present, even if the rock is completely homogeneous and isotropic. The second signal is called the interfacial signal because it arises at interfaces between rock types where the symmetry of the charge distribution within the seismic wave is broken. There results an electric field which propagates away from the interface with the speed of an electromagnetic wave and provides amplitude variations similar to that of an electric dipole positioned at the heterogeneity directly under the seismic source. It should be noted that seismoelectric conversion has been observed to be caused by compressional, shear and Stoneley waves, but research tends to focus on the compressional waves because they provide the strongest interfacial seismoelectric signals.

Hence, it is possible, in principle to perturb a layered Earth with a seismic pulse, then to measure the resulting electrical signals as a function of offset. The interfacial seismoelectric method has recently been used to successfully image the vadose zone of a sand aquifer, monitor hydro-fracturing of a geothermal reservoir, and in a number of borehole studies. Downhole applications represent a particularly active area of research as shown by the large number of patents in that area. However, most of the detailed research remains locked away in various exploration, production, and service companies. Here we have chosen one example of the application of the seismoelectric phenomenon from Australia where vertical seismoelectric profiling (VSEP) has been carried out in boreholes in a sandy aquifer.

Vertical seismoelectric profiling in boreholes

In one recent study by Dupuis et al. (2009) in Australia, vertical seismic profiling (VSP) and vertical seismoelectric profiling (VSEP) measurements were carried out using a borehole electrode array in an unconfined calcareous sandy aquifer (Figure 3). In this work two PVC-cased boreholes with long slotted intervals were used. Their results have shown that it is possible for both coseismic and interfacial seismoelectric conversions to be measured in a borehole environment where the source-receiver geometry provides separation between the interfacial and cosesimic signals.

Dupuis et al. found interfacial signals that were generated in the vicinity of the water table. In both cases the water table was approximately coincident with the upper surfaces of zones of partial cementation, and it is thought that the generation of the interfacial seismoelectric signals is caused by the combination of the contrast in acoustic impedance between the cemented and noncemented rocks together with the change in water saturation and electrical conductivity associated with the water table.

In Figure 3, the VSP direct P-wave arrival is shown by line A for both boreholes, and one can see the associated coseismic arrival in the seismoelectric data of the VSEPs (also shown by line A). The VSP data also show lower velocity tube waves, and these tube waves are also related to coseismic arrivals. The interfacial sesimoelectric conversion is shown in the VSEPs as line B; it arrives simultaneously at all receivers irrespective of their depth and is much smaller than the coseismic signal, decaying quickly with depth.

Although it is not immediately clear from Figure 3, the data from borehole P220 show spatial and temporal variations in the polarity and amplitude of the seismoelectric signal. The authors indicate that this can be explained intuitively by considering how relatively short dipole receivers in the borehole sample the electrical field produced by an expanding vertical bipole-like source. The logic is consistent with existing conceptual models of seismoelectric conversion at interfaces.

Conclusions and future directions

The overall finding is that the study of electrokinetic and seismoelectric properties of porous media has a potentially huge application set. The fundamental origin of the phenomena is well understood at least conceptually and qualitatively. The detailed theory for the steady-state regime has been well known for a long time, and this theory has supported many applications within life sciences research. The development of theory for the AC regime is rudimentary, just as the theory behind AC electrical conduction in porous media is also underdeveloped.

There has been a moderate number of high-quality laboratory experimental studies, but the results are minor when compared to the huge number of possible applications. The result is that the detailed electrokinetic and seismoelectric properties of rocks, and porous media in general, are not reliably known. This lack of data is even more acute when it comes to the AC regime, where almost no high-quality data exists. Researchers at Universite Laval have, however, recently developed equipment for measuring the DC and AC electrokinetic properties of rocks, soils, and sands which should be producing results in 2010. We recommend that other fundamental studies be done to examine the dependence of the electrokinetic and seismoelectric properties of rocks and other porous media in both the DC and the AC regime. It is particularly important to know how changes in temperature, electrolyte chemistry, salinity and pH, matrix mineralogy and saturation affect the physics. TLE

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