Monitoring Fluid Flow during Reservoir Stimulations with Surface Electric Self-Potential Measurements

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Introduction

Reservoir hydraulic stimulations usually generate significant microseismic activity but also electric potential variations : self-potential (SP) anomalies of several mV that correlate temporally to deep reservoir fluid flow have been observed (e.g. Marquis *et al.,* 2002). The standard interpretation of these SP signals is that they originate from electrokinetic processes as water circulates through fractures within the reservoir.

In this paper, we illustrate the possibilities of surface SP monitoring with examples from both hydraulic and acid stimulation experiments of the geothermal reservoir of the Soultz (France) site. We show that surface SP measurements are complementary to borehole pressure and surface and borehole microseismic data and provide key information on the overall dynamics of fluid flow within a reservoir during and after a stimulation.

Electrokinetic Processes in Reservoirs

Streaming Potentials are electric potentials generated by the electrokinetic (EK) interaction of a fluid flowing through a porous medium. The pore fluid is chemically in equilibrium with the rock matrix and this chemical interaction creates ion accumulations at the rock/fluid interface. Thus, when a fluid flows through this porous medium, it moves the charged ionic species and generates a drag current density. If no other external electric current sources exist, this “convection” current is balanced by a conduction current to ensure electric charge conservation. This conduction current is responsible for electric potential anomalies in the rock known as streaming potentials. The electric potential V in the rock can be obtained from the Helmholtz-Smoluchowski equation:

$$\vec{\nabla} V = \frac{\varsigma \varepsilon_f}{\sigma_f \eta_f} \vec{\nabla} P \qquad (1)$$

where P is the pore pressure, σ_f, ε_f, η_f are the fluid electrical conductivity, dielectric permittivity and viscosity respectively, and ζ is the so-called zeta potential. For most water-rock systems, $\zeta < 0$.

The principles of the method are shown in Fig. 1. The electric potential is measured with unpolarisable Pb/PbCl$_2$ electrodes at a sample rate of 1 per minute. We point out that as SP is a potential-field method, each measurement integrates the effect of all electrokinetic sources and therefore is representative of the overall hydrodynamics of the reservoir. Hence, a time-lapse SP survey gives insight into fluid flow dynamics at the reservoir scale.

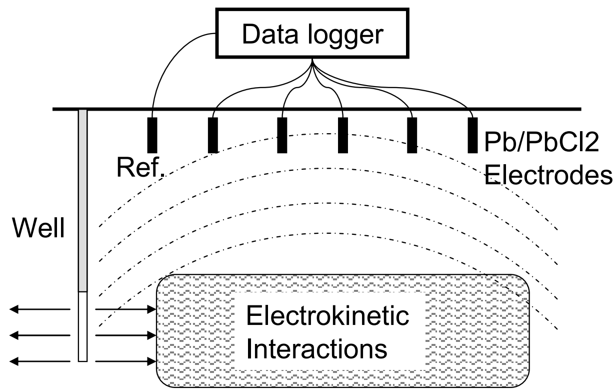

Figure 1. Principles of SP monitoring during a stimulation. When fluid is injected (or produced) in the well, electrokinetic effects produce electric potential variations (dashed curves) that are measured by the electrodes.

Hydraulic Stimulation

In the summer of 2000, a hydraulic stimulation was conducted to develop the geothermal reservoir at depths between 4400 and 5000 m: 23 000 tons of water were injected at flow rates up to 50 kg/s, yielding overpressures around 13 MPa (Fig. 2 bottom). One week after shut-in, a test of injectivity was performed with the injection of 4,500 tons of fresh water at flow rate up to 30 kg/s.

We identify a long-term electric potential variations (Fig. 2 top) of up to 4 mV strongly correlated with the water injection phases and the overpressure (Fig. 2 bottom) and also the seismic event rate (Fig. 2 centre). This behaviour is expected from electrokinetic theory as high injection rates produce high pressure gradients. Electric potential acts as a proxy for fluid flow.

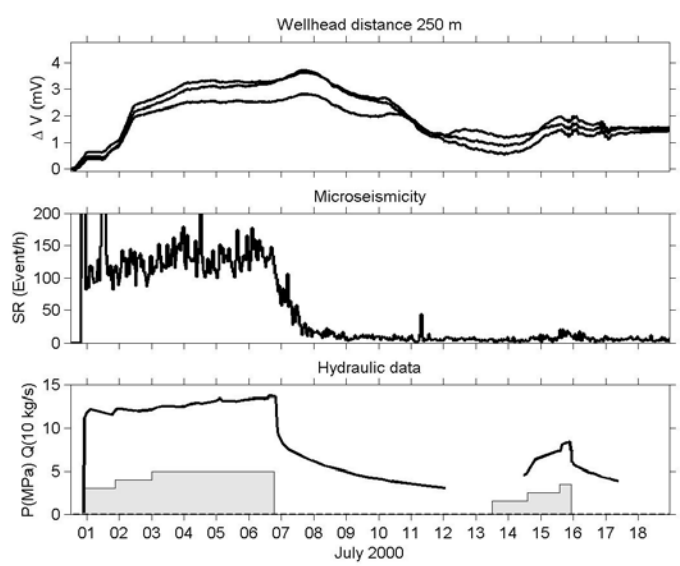

Figure 2. Top: surface electric potential (mV); centre: microseismic event density (/h); bottom: overpressure (MPa) at 4600 m depth (line) and water injection rate (x10 kg/s, boxes) for the 2000 hydraulic stimulation.

The situation is however quite different after shut-in (July 7th): the overpressure and seismic event rate drop rapidly while the SP decreases at a much lower rate. This slow decay of SP indicates that fluid flow persists in the reservoir long after shut-in. This significant post-shut-in fluid flow explains the occurrence of several large microseismic events (12 events with M > 1.8) up to one month after shut-in.

Why do overpressure and SP drop at different rates? Because of the different observation scales of both methods: pressure measurements describe fluid flow dynamics within the zones hydraulically connected to the sensor whereas SP measurements integrates the effect of the fluid flow within the whole reservoir (Darnet et al., 2006).

Acid Stimulation

In the spring of 2005, three injections were realised (bottom of Fig. 3): the first and the third consisted in 5000 tons of fresh water and the second in 5000 tons of an HCl solution. The success of the acid stimulation can be seen in the central panel of Fig. 3: for the same flow rate, the wellhead pressure in the injection well is of 13 MPa before the stimulation and of only 9 MPa after. We point out that the pH of the in situ brine in the Soultz reservoir is already quite low (4.8) and that the pH of the injected fluid is between 1.7 and 2.0. The maximum flow rate is 30 kg/s.

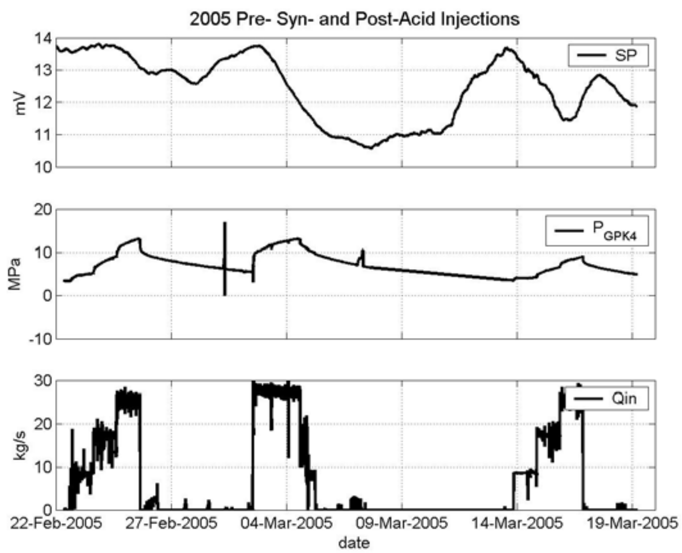

Figure 3. Top: surface electric potential (mV); centre: wellhead overpressure (MPa); bottom: injection rates (kg/s) of water (Feb. 23-25), acid (Mar. 2-6) and water (Mar. 14-17) for the 2005 acid stimulation.

The SP signal during the acid stimulation is shown in Fig. 3. In contrast to what is obsereved for water hydraulic stimulation, injection of acid (Mar. 2-6) produces a 3 mV drop in SP. Furthermore, the SP signal continues to decrease long after shut-in and the base level of 13-14 mV is only recovered 8 days after the end of the acid injection. This implies that the acid has been active, i.e. dissolving calcite, for about one week.

The pattern of SP variations is similar to what has been observed in hydraulic stimulations but with an opposite polarity, as if the injection of acid decreased the electric potential. If we associate the SP signals to electrokinetics, this implies that the zeta potential in equation (1) is positive, i.e. the conduction (i.e. ohmic) current follows fluid flow.

Actually this observations is in agreement with laboratory measurements on crushed sandstone by Lorne et al. (1999) who have shown that for extremely low pH values (less than 2.5; Fig. 4), the zeta potential is positive. Our data are therefore one of the first field observations of reverse electrokinetics.

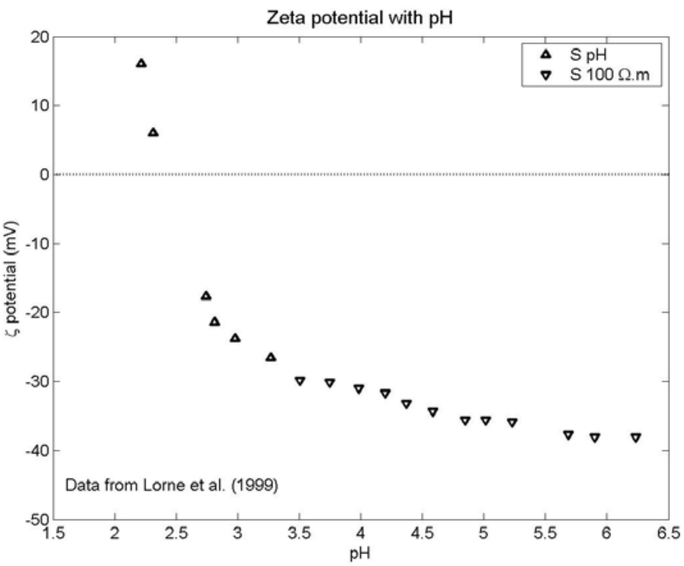

Figure 4. Zeta potential (mV) as a function of pH for fluid-sandstone (triangles), fluid-quartz (circles) and fluid-granite (dots). Note the positive values for very low pH.

Prior to the third injection stage, the surface electric potential has returned near its base level at 14 mV. As the water injection rate increases, we observe again a decrease of the surface electric potential of about 2 mV. This decrease is not expected: fresh water is injected and so one would expect an increase in SP, as shown in Fig. 2.

The origin of this SP signal is not necessarily electrokinetic. Indeed, the dissolution of the calcite in the fractures by the acid increases dramatically the ionic content of the fresh water injected afterwards. We therefore interpret this anomalous SP signal as an ongoing electrochemical process, not related to electrokinetics.

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References

Darnet, M., Marquis, G. & Sailhac, P. , 2006, Hydraulic stimulation of geothermal reservoirs: fluid flow, electric potential and microseismicity relationships: Geophys. J. Int., **166**, 438-444.

Lorne, B., Perrier, F. and Avouac, J.P., 1999, Streaming potential measurements 1. Properties of the electrical double layer from crushed rock samples: Journal of Geophysical Research, **104**, 17857-17877.

Marquis, G., Darnet, M., Sailhac, P., Singh, A.K. and Gérard, A., 2002, Surface Electric Variations Induced by deep Hydraulic Stimulation: an Example from the Soultz HDR site: Geophysical Research Letters, **29**, doi:10.1029/2002GL015046.