NUMERICAL MODELLING OF SELF-POTENTIAL FOR ENHANCED GEOTHERMAL SYSTEMS

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Introduction. Geothermal resources represent a sustainable and potentially competitive alternative to fossil fuels. Enhanced geothermal system (EGS) technologies, in particular, provide a powerful way to produce geothermal electric energy in almost every area of the world. EGSs exploit hot rock systems with low water content, with the economic feasibility depending on the drilling costs needed to reach a suitable temperature. Despite its great potential, EGS exploitation is still perceived as environmentally threatening, because of the problems posed by unwanted induced seismicity above a certain magnitude threshold (MIT Report, 2006). Such events can more frequently occur due to hydraulic stimulation that is aimed at creating a permeable reservoir in EGS systems. Such a negative perception of EGSs is mainly due to the Basel earthquake of magnitude ML 3.4 that occurred in 2006 December. Although this event did not produce serious damage, it was strongly felt by the population because the geothermal site was located in the center of the city (Haring *et al.,* 2008; Ripperger *et al.,* 2009). Less known but equally interesting cases have also been described in the literature over the last few decades (see Majer *et al.,* 2007, and references therein). Hence, interpreting the mechanisms of induced seismicity and understanding ways of mitigation is important to allow the promotion of geothermal EGS exploitation worldwide (Giardini, 2009). The hot-dry-rock site of Soultz-sous-forets is one of the best examples of the experience of EGSs. The permeability enhancement of this reservoir was obtained through the drilling and subsequent stimulation of four wells that reached depths of up to 5km (Portier and Vuataz, 2009). A complex sequence of fluid injection was performed over several years, to enlarge the fracture system of the basement rock, composed mainly of granite, and to enhance its permeability. The stimulation of this multi-well structure allowed the creation of natural heat exchangers and the generation of stable commercial electricity. The development of the Soultz power plant and its several related scientific projects have been fully described in the literature. The geophysical prospecting consisted of a series of passive seismic tomography investigations (Charlety *et al.,* 2006; Cuenot *et al.,* 2008; Dorbath *et al.,* 2009), as well as electromagnetic imaging (Geiermann and Schill, 2010). Also, geochemical data were collected (Sanjuan *et al.,* 2010), the rock permeability and the fracture system were described (Genter *et al.,* 1997; Evans *et al.,* 2005a, 2005b), and the regional stress field was estimated (Cuenot *et al.,* 2006). Furthermore, the whole drilling process was accurately described for each well through a series of technical reports (Baria *et al.,* 2004). These reports thus provide highly detailed records of the different phases of the artificial stimulation that was carried out to create the permeable reservoir, including the flow rates, the head pressures of the boreholes, the temperature profiles and the distribution and magnitude of induced seismic events. In this paper we use this large amount of information as a basis for testing the capability of a classical applied geophysical method, so called self-potential (PS) to forecast the induced seismicity related to deep fluid injection during well stimulation. The self-potential method (SP) is one of the oldest of all the geophysical techniques. It consists of monitoring or mapping passively the electrical field existing at the ground surface of the Earth. In this paper the distribution of SP associated with a real pumping stimulation at Soultz-sous-Forets has been numerically evaluated and successively compared with induced seismicity occurred during the stimulation process. To this aim a numerical procedure has been used allowing the reconstruction of the thermodynamic evolution of the reservoir in terms of pressure and temperature. This kind of procedure has been already employed to evaluate the Coulomb Stress changes on preferred fault mechanism (Troiano *et al.*, 2013) and its matching with the induced seismicity recorded during the fluid injection. The reconstructed changes in pressure and temperature are subsequently considered as electrical sources that are heterogeneously distributed in the whole volume responsible of electric potential generated. In particular the electric signal derived from considering only the streaming potential originated from groundwater flow has been firstly studied and compared with experimental data recorded at Soultz. After the effect of temperature has been taken into account to complete our study of SP in that area and we underline the effect that bring major contribution, within sources considered. In the end the obtained distribution of electric potential has been compared with the density of seismic events recorded at Soultz-sous-Forets for the same sequence of injection.

The self potential method. In recent years, the self-potential (SP) method has been applied to study the dynamics of fluid flow within natural water and/or hydrocarbon reservoirs. This technique was first applied as mapping tool of water flow in aquifers (e.g. Ogilvy *et al.*, 1969; Bogoslovsky and Ogilvy, 1970, 1973) and in geothermal areas (e.g. Corwin and Hoover, 1979). The SP method was later used as a monitoring tool of fluid flow within geothermal reservoirs (Ishido *et al.*, 1983; Kawakami and Takasugi, 1994; Ushijima *et al.*, 1999; Murakami *et al.*, 2001) and more recently within aquifers (Perrier *et al.*, 1998; Pinettes *et al.*, 2001). Moreover, several theoretical and laboratory studies (Ishido and Mizutani, 1981; Morgan *et al.*, 1989; Sprunt *et al.*, 1994; Jouniaux and Pozzi, 1995; Bernabe, 1998; Revil *et al.*, 1999a, 1999b; Marino *et al.*, 1999; Lorne *et al.*, 1999a, 1999b; Reppert, 2000) were conducted in order to better understand electrokinetic phenomena in rocks for various chemical and thermal conditions. Numerical modeling schemes were also developed (Sill, 1983; Wurmstich and Morgan, 1994; Ishido and Pritchett, 1999) in order to combine all these studies and better interpret SP anomalies induced by fluid flow in reservoirs. The main contributions to the self-potential signals are (1) the streaming potential related to groundwater flow, (2) the diffusion potential related to gradients of the chemical potential of ionic species, (3) the thermoelectric effect related to the influence of the temperature upon the chemical potential of charge carriers, and (4) the electro-redox effect associated with bodies and contaminant plumes that are rich in organic matter. A general formulation of this problem for a porous material has been developed recently by Révil *et al.* (2002). Considering a porous media composed by grains of mineral and pores filled by an electrolyte in chemical equilibrium with grains, the chemical interaction between grains and electrolyte originates an electrical double layer. In the case of the majority of minerals composed by grains with beam > 0.1 μm the thickness of this layer can be assumed smaller than the rays of pores and grains (electrical double layer plane and fine). In addition, the fluid flow through a porous media can be considered as laminar. The constitutive relationship of electrical current density and velocity of the fluid are (Révil *et al.,* 2002):

$$\vec{J} = -l_{11}\vec{\nabla}V - l_{12}\left(\vec{\nabla}P - \rho_f\vec{g}\right) \tag{1}$$

$$\vec{U} = -l_{21}\vec{\nabla}V - l_{22}\left(\vec{\nabla}P - \rho_f\vec{g}\right) \tag{2}$$

V is the electric potential [V], P is the fluid pressure [Pa], g is the gravity acceleration [m/s^2] and ϱ_f is volumetric mass of the fluid .

The terms l_{ij}, inside Eqs. (1) and (2), represent the flux coupling coefficients, generally considered as constant to account the linearity experimentally observed between fluid flux and its generating forces. The coefficient l_{12} and l_{21} can be assumed as equals (Révil *et al.*, 2002) due to the reciprocity law of Onsangar (De Groot and Mazur, 1962). l is the electrokinetic coupling coefficient, determining both the intensity of fluid mass generated by a gradient of electrical potential (electroosmosis) and the electrical flux induced by a pressure gradient (electrokinetism). In the case of homogeneous isotropic porous media the l coefficient is:

$$l = -\frac{\varepsilon_0\varepsilon_r\zeta}{\eta F} \tag{3}$$

where F is the ratio between electrical conductivity of fluid and electrical conductivity of porous media, ε_0 is the vacuum dielectric permittivity ($8.854 x 10^{-12}$F/m), ε_r is the fluid dieletric permittivity , η is the fluid dynamic viscosity [Pa.s], ζ is the so-called "zeta-potential" [V].

Moreover, due to the Ohm's law, the l_{11} coefficient could be assumed as equal to the electrical conductivity of porous media [S/m] and, due to the Darcy's law, the l_{22} coefficient could be assumed as equal to its permeability [m^2].

With this kind of assumption, Eqs. (1) and (2) could be rewrite as :

$$\vec{J} = -\sigma\vec{\nabla}V - l\left(\vec{\nabla}P - \rho_f\vec{g}\right) \tag{4}$$

$$\vec{U} = -l\vec{\nabla}V - \frac{k}{\eta}\left(\vec{\nabla}P - \rho_f\vec{g}\right) \tag{5}$$

Eq. (4) is the generalized Ohm's law. Its first term coincides with conduction electrical current (Ohm's law) while the second one corresponds to convection electrical current induced by a displacement of electrical charges existents in the double layer. Eq. (5) is the generalized Darcy's law. Its first term describes the fluid flow induced from an electrical potential difference while the second term embodies a flux of fluid originated by a pressure gradient. Considering Eq. (4) and combine it with conservation of total current density in the absence of external sources it follows:

$$\vec{\nabla}\left(\sigma\vec{\nabla}V\right) = -\vec{\nabla}\left[l\left(\vec{\nabla}P - \rho_f\vec{g}\right)\right] \tag{6}$$

In this diffusive equation the right term represents electrical sources generated by electrokinetism. Eq. (6) can be developed as:

$$\nabla^2 V = -\frac{\vec{\nabla}\sigma}{\sigma}\vec{E} - \frac{1}{\sigma}\left[\vec{\nabla}l.\vec{\nabla}P - \rho_f\vec{\nabla}l.\vec{g} - l\nabla^2 P\right] \tag{7}$$

Being the electrokinetic coupling coefficient constant (Darnet *et al.*, 2003), only the last source of the right term of the Eq. (7) has to be considered. Also the conductivity of the underground has to be taken into account, in the case of self-potential generated in heterogeneous media. In this paper, a heterogeneous conductive model has been adopted for the underground that consider the resulting of a magnetotelluric survey realized in the area (Geierman *et al.*, 2010). l, as stated above, represents the electrokinetic coupling coefficient of the injected fluid. In most cases, instead of l, the streaming potential coupling coefficient C is considered, that results equal to l divided by the rock electrical conductivity σ_r , that is only temperature- and salinity-dependent . Following Revil *et al*. (1999b),

$$C = \frac{\varepsilon_f\zeta}{\eta_f\sigma_f} \tag{8}$$

Where η_f is the fluid dynamic viscosity [Pa.s], ε_f is the fluid dielectric permittivity [F/m], σ_f is the fluid electrical conductivity [S/m] and ζ is the "zeta-potential" [V] at the fluid/matrix interface generated by the chemical interaction of the rock and the fluid. The fluid viscosity and dielectric constant are only temperature-dependent , while the fluid electrical conductivity is temperature- and salinity-dependent. The zeta potential is also temperature- and salinity-dependent and we used the results of Revil *et al*. (1999a) for quartz-water systems. To estimate streaming potential coupling coefficient, Darnét *et al*. (2003) used the downhole temperature and salinity of injected fluid during and after pumping stimulation. At the start of the stimulation experiment, when brine is injected, C is weak (less than 2 mV/bar) but as soon as fresh water is injected, it increases and reaches the value of 200 mV/bar, remaining constant until shut-in. After shut-in, even if no more fluid is injected, C increases further caused by thermal effect. The average value of C, around 200 mV/bar, can be considered a good approximation for

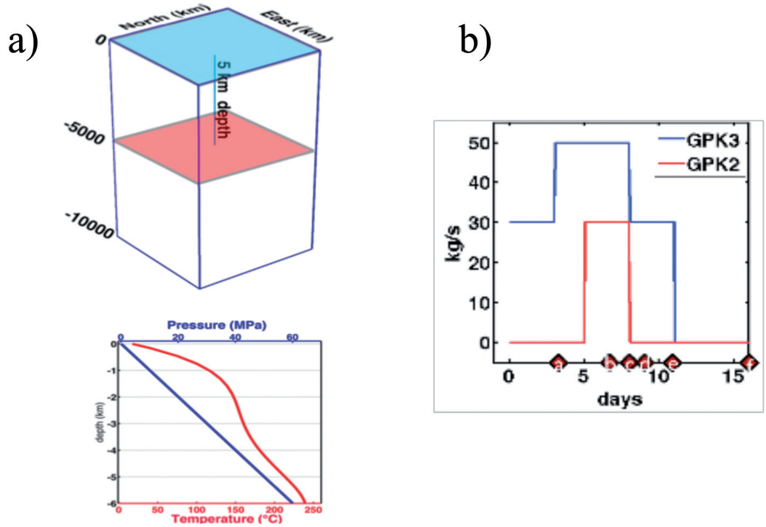

Fig. 1 – a) Top: Sketch of the simulation volume. Blue plane, Earth surface; red plane, injection plane. Bottom: pressure and temperature initial conditions. b) Simplified stimulation functions for the GPK2 and GPK3 Soultz-sous-Forets wells, representing the rates of injected water. (a–f) Times of the stimulation cycle shown.

the streaming potential coupling coefficient for the whole injection cycle, following Darnet *et al*. (2003). Once the value of C and the fluid pressure field are both known, it is possible to compute the electric current sources from Eq. (7) and to solve the electrical problem calculating the electric potential induced by the stimulation process.

Method. Our method of analysis consists of a two-step procedure. In the first step, injection of water is simulated (Pruess, 1991, 1999) in a homogeneous medium, approximating a crystalline granite basement compatible with the deep structure of the Soultz-sous-Forets (France) EGS site. The modeled 3D physical domain and the imposed initial conditions are shown (Fig.1a).

Water at ambient condition is injected at a variable flow rates, in order to reproduce the effects of a real stimulation experiment realized in the GPK2 and GPK3 wells of the geothermal field during the 2003. An essential scheme of this stimulation process is given in Fig.1b.

In such a way the pressure and temperature changes at each point in the medium has been obtained, at six distinct times (Troiano *et al*., 2011, 2013). The spatial gradient of the induced pressure field in the whole volume has been successively considered as source of electric potential anomalies, due to the so called electrokinetic effect linked to the pressure gradient in the medium. Fluid flow through a porous medium generates, in fact, an electric potential variation due to the electrical interaction between the fluid and the electrical double layer at the pore-mineral interface (Helmholtz, 1879). Fluid injection and/or circulation within geothermal reservoirs can produce surface Self-Potential (SP) anomalies of several mV that are correlated in space (e.g., Ushijima *et al*., 1999) and in time (e.g., Ishido *et al*., 1983; Marquis *et al*., 2002) to reservoir fluid flow. The electric potential changes induced by fluid injection has been reconstructed resolving the Poisson equation by finite element code. A source term of the kind:

$$\nabla^2 V = -\frac{\vec{\nabla}\sigma}{\sigma}\vec{E} - \frac{1}{\sigma}\left[-l\nabla^2 P\right] \tag{9}$$

has been imposed, where P represents the fluid pressure, σ the electrical conductivity, and l represents the coupling term, expressed in A/m^2, characterizing the electrical current density produced in response to the unit hydraulic gradient. The coupling coefficient has been assumed as a constant during the stimulation, in agreement with literature data (e.g. Darnet, 2003).

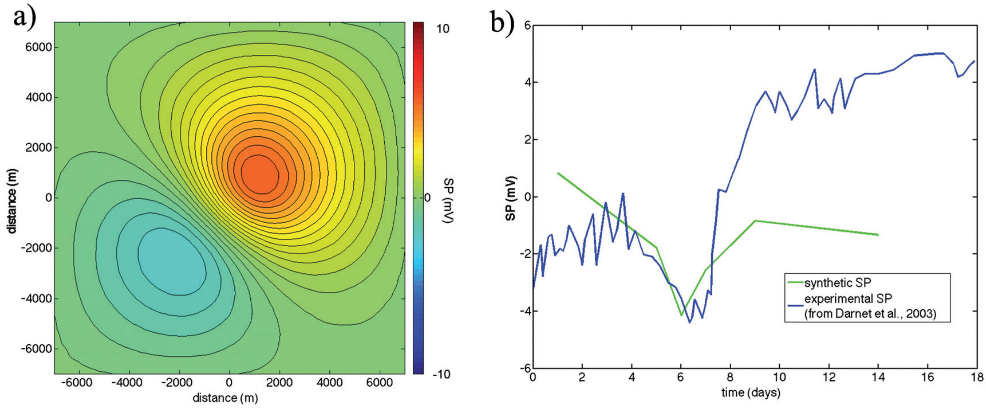

Fig. 2 – a) Typical trend of the SP anomalies related to the stimulation cycle. b) Comparison between numerical (green line) and real (blue line) SP anomalies related to the stimulation cycle of Fig. 1b.

Appropriate boundary conditions on the electrical potential or the electrical current density has been considered.

Results and discussion. The effects of the fluid injection sketched in Fig. 1b has been analyzed reconstructing the electric potential changes on the ground surface at six distinct time (indicated as a-f) spanning the whole stimulation process. SP are characterized by a typical dipolar trend, with a general intensity of order of mV (Fig. 2a).

The electric potential grows up when the rate of fluid injection increases, at times a-b-c-d, after decreasing in correspondence of reduction of the fluid injection rate (or well shut-off), at times e and f. The dipolar trend reconstructs the pattern of groundwater flow showing a privileged direction of fluid flows, aligned to the regional tectonic load. The electric signal has been compared with experimental data recorded at Soultz-sous-Forets. A good agreement has been found, firstly for intensity of signal (Fig. 2b). In effect, the synthetic potential presents the same order of magnitude of typical electric potential recorded. Both numerical and experimental signal show a linear trend for small injection rate, falling sharply in correspondence of wells shut-off. Successively, a strong increase of electric potential is present, induced by residual circulation of groundwater flow in the geothermal reservoir. It is worth noting how this persistence of fluid flows explains the occurrence of seismic events also several days after the end of wells stimulation. To the aim of evidencing such correlation between SP anomalies and induced seismicity, the obtained distribution of electric potential has been compared with the density of seismic events recorded at Soultz-sous-Forets during the wells stimulation, retrieving a good analogy (Fig. 3).

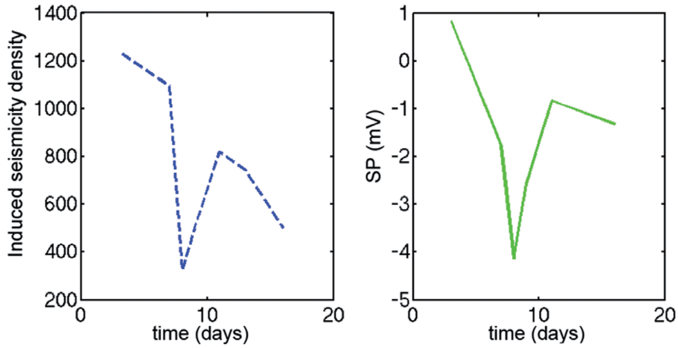

Fig. 3 – Comparison between induced seismicity density (blue line, left panel) and numerical SP anomalies (green line, right panel) related to the stimulation cycle of Fig. 1b.

In particular, in correspondence of flow rates reduction, a strong decay of both seismic density events and electric potential magnitude is observed. Successively, a rapid increase of electric potential corresponds with a similar raise of number of seismic events. This behavior confirms the linking between groundwater flow in geothermal media, persisting also after the wells shut-off, the electric potential anomalies and the induced seismicity. This confirms also the capability of SP method to represents an useful monitoring tools in evaluation of the seismic hazard.

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