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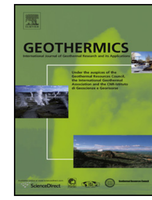


# Fluid injection in Enhanced Geothermal Systems: a study on the detectability of self-potential effects and on their correlation with induced seismicity

A. Troiano[a,*], M.G. Di Giuseppe[a], A. Monetti[a], D. Patella[a,b], C. Troise[a], G. De Natale[a]

[a] Osservatorio Vesuviano, Istituto Nazionale di Geofisica e Vulcanologia, Naples, Italy
[b] Department of Physics, University Federico II, Naples, Italy

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ABSTRACT

We present a numerical modeling aimed at investigating nature and role of the self-potential (SP) anomalies induced by water injection in boreholes at the Soultz-sous-Forêts (SsF) hot dry rock enhanced geothermal field. The overpressure due to the fluid stimulation is considered as source of the streaming potential effects in rocks, responsible on their turn of the SP anomalies observed at the ground surface. The numerical simulations have been realized by a combined application of the TOUGH2 and Comsol Multiphysics codes, which had already been successfully used to predict Coulomb stress changes in rocks induced by a fluid injection cycle. Two synthetic cases are investigated. At first, a simulated injection cycle in a single borehole has been modeled, consisting in the reconstruction of the overpressure and SP temporal and spatial evolutions induced by the hydraulic stimulation of the rock. The main result is that the front of the SP anomaly follows the overpressure front, with the time delay between the two fronts decreasing at increasing distance from the well. The second case takes into consideration a real injection experiment performed in 2003 at SsF, which has allowed to examine the induced seismicity. The simulated SP response to this real injection cycle shows that the SP temporal evolution is essentially a post-seismic effect. The conclusion from the simulations is that SP measurements can be used to localize the main features of the fluid flow into the reservoir.



## 1. Introduction

Conventional hydrothermal resources have been largely exploited in the past century and nowadays geothermal energy is increasingly being explored as an attractive energy source, representing a sustainable and competitive alternative to fossil fuels. However, only a fraction of the thermal energy of the earth can be utilized to produce electricity and the utilization of this energy has been limited to areas where geological conditions permit a carrier (water in the liquid or vapor phase) to transfer the heat from deep hot zones to or near the surface, thus creating geothermal resources. Enhanced geothermal system (EGS) technologies provide a powerful solution to produce electric energy in almost every area of the world, exploiting 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, 2006). In effect, seismicity is a geological phenomenon that naturally occurs in active geothermal areas and normal production operations can create low-magnitude events (known as microearthquakes) that typically cannot be detected without sensitive equipment. The hydraulic stimulation that is aimed at creating a permeable reservoir in EGS systems, instead, make seismic events occurrence more frequent (see Majer et al., 2007; and references therein). As a consequence, a negative perception of EGSs results, as in the case of the Basel earthquake of magnitude ML 3.4 that occurred in December 2006. 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 (Häring et al., 2008; Ripperger et al., 2009) and the related activities have been dismissed. Hence, interpreting the mechanisms of induced seismicity and understanding ways of mitigation is important to allow the promotion of EGS exploitation worldwide (Giardini, 2009).

* Corresponding author.
*E-mail address:* antonio.troiano@ingv.it (A. Troiano).

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The hot-dry-rock site of Soultz-sous-Forêts (SsF), France, 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 5 km (Portier et al., 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 development of the SsF 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 (Charléty 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,b), 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.

To understand and quantify the processes associated with groundwater flows, a significant attention has been paid in the last decades to the numerical modeling of the phenomena, due to the considerable heuristic insight that can be achieved from this approach. In the framework of the EGSs analysis, a numerical procedure has been utilized in order to evaluate the effects of deep fluid injections and withdrawal in the SsF system (Troiano et al., 2013). Such a kind of analysis, derived from a formerly realized modeling of the ground uplift due to the hydrothermal system reactivation in the Campi Flegrei caldera, Southern Italy (Troiano et al., 2011), has been applied to the SsF case in order to reconstruct the thermodynamic evolution of the reservoir in terms of Coulomb Stress (CS) changes on preferred fault mechanism, obtaining a good interpretation of the observed induced seismicity.

On the other hand, a wide range of physically observable parameters can be affected by deep fluid injection and numerical modeling represents a quantitative tool to understand their meaning as predictors of the boreholes stimulation related phenomena. Among them, the electrical field existing at the ground surface of the earth could be of great relevance, being known for a long time that fluid flows through a porous medium generate changes of the natural electric potential (*e.g.* Bogoslovsky and Ogilvy, 1973; Patella and Di Maio, 1991; Perrier et al., 1998; Revil et al., 1999a,b; Kulessa et al., 2003a,b; Rizzo et al., 2004; Titov et al., 2005). The self-potential (SP) monitoring is one of the oldest geophysical techniques. This method has already been applied to study geophysical effects linked to fluid flow, and related applications include volcanology (Zlotnicki and Le Mouël, 1990; Di Maio and Patella, 1994; Di Maio et al., 1996, 1998), geothermics (Corwin and Hoover, 1979), hydrology (Sill, 1983) and earthquake phenomena (Patella et al., 1997; Varotsos et al., 1999; Lapenna et al., 2000). Its association with the groundwater flow has been significantly investigated in the last decades. Sill (1983) proposed an approach to the modeling of electrical effects originated by primary heat and fluid flows. Ishido and Pritchett (1999) proposed a numerical postprocessor to compute the SP space and time distribution resulting from simulated histories of underground conditions of fluid pressure, temperature, vapor saturation and dissolved salt concentrations. Ushijima et al. (1999) developed a 4-D fluid flow tomography method based on inversion of SP anomalies to monitor fluid flow behaviors during forced water injection through a borehole. Titov et al. (2005) proposed a modeling of the SP signals associated with a pumping test in an unconfined aquifer. Mahardika et al. (2012) developed a joint seismic and electrical data inversion code to investigate the electrical effects associated with the occurrence of a fracking event in a two-layer system. Haas et al. (2013) made analogical laboratory experiments of water injection in a well aimed at monitoring SP and acoustic emissions. Also in Revil et al. (2015) the same approach is followed, adding also a 4D inverse modeling of the source using both deterministic and stochastic approaches. They also performed forward numerical simulations in order to assess the underlying physics of the causative source of the observed SP anomalies and how they are related to the flow of the water phase. In all of these papers, inverse modeling tools were also developed in order to use the electrical information to monitor the hydromechanical disturbances.

The stimulation of EGS systems by water injection in boreholes has also been specifically analyzed in terms of SP induced anomalies. Marquis et al. (2002) report electric potential anomalies up to 5 mV, measured in the SsF hot dry rock test site at two points distant 250 m and 500 m from a reference electrode located near the injection wellhead. The electrograms were modeled considering a sudden overpressure flow at depths between 4400 and 5000 m within a high resistivity half-space with a high-conductivity vertical well casing acting as an equipotential. Darnet et al. (2006) discuss the SP effects at SsF and their link to the induced seismicity during the geothermal reservoir deep stimulation. They assess that the conductive casing plays a decisive role in making the surface SP anomalies measurable also considering a 5 km injection depth.

In this paper we show the results from an electric modeling of a complex water injection experiment realized in 2002 at the SsF test site, previously used by Troiano et al. (2013) to evaluate the mechanical effects of the hydraulic stimulation in terms of induced seismicity. The induced pressure field considered in that analysis is assumed to be the source term also for the electric currents generating the SP anomalies at the earth's surface. The novelty of the present approach consists in considering the whole fluid flow pattern as source. Indeed, the overpressure field, estimated considering both the mass and energy contributions, *i.e.* both the conductive and convective terms, was shown to be characterized by a volumetric extension of more than 1 km radius, with a heterogeneous spatial distribution very far from a conventional spherically symmetric point source (Troiano et al., 2013). We consider this approach more appropriate to reconstruct the electric phenomena. Fluid flows may, in fact, be subjected to complex interactions in porous media also at great distances from the injection point, especially where convective cells, permeability contrasts and/or strongly irregular fluid paths are present.

As a first test, a synthetic case has been modeled, after which a real injection process has been simulated. The distribution of SP signals associated with the fluid stimulation has been compared with the overpressure front originated during the same injection. A further comparison has been afforded, with the aim of evaluating the link between fluid flows, SP anomalies and induced microseismicity.

## 2. Outline of the SP theory

In recent years, the SP method has been applied to study the dynamics of fluid flows within natural reservoirs. This technique was first applied as a mapping tool of water flow in aquifers (*e.g.* Ogilvy et al., 1969; Bogoslovsky and Ogilvy, 1970, 1973) and later to monitoring geothermal reservoirs (Corwin and Hoover, 1979; Ishido et al., 1983; Kawakami and Takasugi, 1994; Ushijima et al., 1999; Murakami et al., 2001). Moreover, several theoretical and laboratory studies were conducted in order to better understand electrokinetic phenomena in rocks for various chemical and thermal conditions (Ishido and Mizutani, 1981; Morgan et al., 1989;