Modeling Self-Potential Effects During Reservoir Stimulation in Enhanced Geothermal Systems.

A. Monetti[1], A. Troiano[1], M. G. Di Giuseppe[1], C. Troise[1], G. De Natale[1] and G. Perillo[2]
[1] INGV-Osservatorio Vesuviano, Naples
[2] University of Parthenope, Naples
*Giovanni Perillo: giovanni.perillo@uniparthenope.it

Abstract: Geothermal systems represent a large resource that can provide, with a reasonable investment, a very high and cost-effective power generating capacity. Considering also the very low environmental impact, their development represents, in the next decades, an enormous perspective (MIT Report, 2006). Despite its unquestionable potential, geothermal exploitation has long been perceived as limited, mainly because of the dependence from strict site-related conditions, mainly related to the reservoir rock's permeability and to the high thermal gradient, implying the presence of large amounts of hot fluids at reasonable depth. Many of such limitations can be overcome using Enhanced Geothermal Systems technology (EGS, Majer et al., 2007), where massive fluid injection is performed to increase the rock permeability by fracturing. This is a powerful method to exploit hot rocks with low natural permeability, otherwise not exploitable. Numerical procedures have already been presented in literature reproducing thermodynamic evolution and stress chsnges of systems where fluids are injected (Troiano et al., 2013). However, stimulated fluid flow in geothermal reservoirs can produce also surface Self-Potential (SP) anomalies of several mV. A commonly accepted interpretation involves the activation of electrokinetic processes. Since the induced seismicity risk is generally correlated to fluid circulation stimulated in an area exceeding the well of several hundreds of meters, the wellbore pressure values can be totally uncorrelated to seimic hazard. However, SP anomalies, being generated from pressure gradients in the whole area where fluids flow, has an interesting potential as induced earthquake precursor.

In this work, SP anomalies observed above the Soultz-sous-Forets (Alsace, France) geothermal reservoir while injecting cold water have been modeled, considering a source related to the fluid flow induced by the well stimulation process. In particular, the retrieved changes of pressure due to well stimulation in the EGS system have been used as a source term, to evaluate the electric currents generating the potential anomalies, using COMSOL Multiphysics. In such a way, SP anomalies generated during the stimulation process at Soultz-sous-Forets have been simulated in order to evaluate the effectiveness of SP monitoring to mitigate the induced seismicity risk.

Keywords: Applied geophysics, geothermal systems, induced seismicity

1. 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 5 km (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 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 (SP), to forecast the induced seismicity related to deep fluid injection during well stimulation. The SP method 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 studied and compared with experimental data recorded at Soultz. 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.

2. Method

Our method of analysis consists of a two-step procedure. In the first step, injection of water is simulated (Pruess, 1991) 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.1).

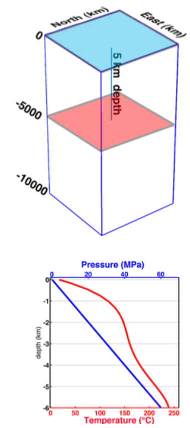

Figure 1. Top: Sketch of the simulation volume. Blue plane, Earth surface; red plane, injection plane. Bottom: pressure and temperature initial conditions are indicated. Initial pressure (blue) and temperature (red) conditions as a function of depth.

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.2.

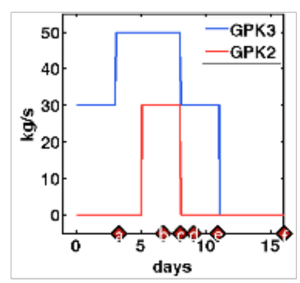

Figure 2. Simplified stimulation functions for the GPK2 and GPK3 Soultz-sous-Forets wells, representing the rates of injected water. (*a*–*f*) Times of the stimulation cycle shown.

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, Troiano et al., 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 the Comsol Multiphysics finite element code. A source term of the kind:

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

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

3. Results and discussion

The effects of the fluid injection sketched in Fig. 2 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.3).

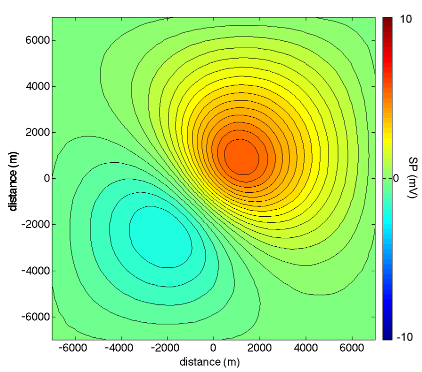

Figure 3. Typical trend of the SP anomalies related to the stimulation cycle of Figure 2.

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.4). 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

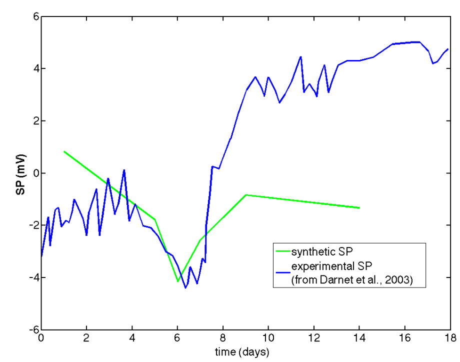

Figure 4. Comparison between numerical (green line) and real (blue line) SP anomalies related to the stimulation cycle of Fig.2.

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.

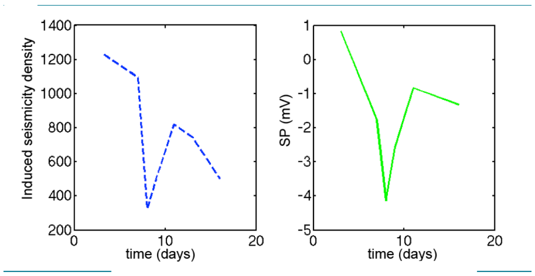

Figure 5. Comparison between induced seismicity density (blue line, left panel) and numerical SP anomalies (green line, right panel) related to the stimulation cycle of Fig.2.

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.

9. References

1. Baria, R. et al., Microseismic monitoring of the world's largest potential HDR reservoir, in Twenty-Ninth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2004).
2. Darnet, M., Marquis, G. and Sailhac, P., Estimating aquifer hydraulic properties from the inversion of surface streaming potential (SP) anomalies, *Geophysical research letters*, **30** (2003)
3. Giardini, D., Geothermal quake risks must be faced, *Nature*, **462**, 848–849 (2009)
4. Haring, M.O., Schanz, U., Ladner, F. and Dyer, B.C., Characterisation of the Basel 1 enhanced geothermal system, *Geothermics*, **37**, 469–495 (2008)
5. Helmholtz, W., *Abhandl. physic. tech. Reichsantalst I*, **925**, 186 (1879)
6. Ishido, Tsuneo, Hitoshi Mizutani, and Kenzo Baba, Streaming potential observations, using geothermal wells and in situ electrokinetic coupling coefficients under high temperature, *Tectonophysics*, **91.1**, 89-104 (1983)
7. Massachussetts Institute of Technology, The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century: An Assessment, MIT Press, MA, USA (2006)
8. Marquis, G., et al, Surface electric variations induced by deep hydraulic stimulation: An example from the Soultz HDR site, *Geophys. Res. Lett.*, **29.14**, 2002
9. Ripperger, J., Kastli, P., Fa ̈h, D. and Giardini, D., Ground motion and macroseismic intensities of a seismic event related to geothermal reservoir stimulation below the city of Basel-observations and modelling, *Geophys. J. Int.*, **179**, 1757–1771 (2009.)
10. Portier, S. and Vuataz, F.D. (Eds), Studies and support for the EGS reser- voirs at Soultz-sous-Foreˆts. Final report April 2004–May 2009, Project financed by State Secretariat for Education and Research (SER/SBF) and Swiss Federal Office of Energy (2009)
11. Pruess, K., TOUGH2—A General Purpose Numerical Simulator for Multiphase Fluid and Heat Flow, L.B.L. Report, Berkeley, CA (1991)
12. Troiano, A., Di Giuseppe, M.G., Petrillo, Z., Troise, C. and De Natale, G., Ground deformation at calderas driven by fluid injection: modelling unrest episodes at Campi Flegrei (Italy), *Geophys. J. Int.*, **187**, 833– 847 (2011)
13. Troiano, A., Di Giuseppe, M. G., Troise, C., Tramelli, A., and De Natale, G., A Coulomb stress model for induced seismicity distribution due to fluid injection and withdrawal in deep boreholes. *Geophys. J. Int.*, **195(1)**, 504-512 (2013)
14. Ushijima, K., H. Mizunaga, and T. Tanaka, Reservoir monitoring by a 4-D electrical technique, *The Leading Edge*, **18**, 1422–1424, (1999)