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On self-potential data for estimating permeability in enhanced geothermal systems

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ABSTRACT

We study the use of hypothetical self-potential (SP) data – more specifically streaming-potential data – for the inversion of subsurface permeability distributions, using the enhanced geothermal system at Soultz-sous-Forêts, France, and a synthetic geothermal hard-rock reservoir as examples. Simulations are carried out using the software SHEMAT-Suite. We perform this study based on results obtained via a massive Monte Carlo approach and additionally use the Ensemble Kalman Filter technique for the inversion. In a first step, we perform forward simulations and assume that SP data is measured along the production and injection wells. The SP monitoring data mainly depend on the near-field (150 m) permeability around these wells. In this case, the SP signal is in good agreement with the distribution of the hydraulic head. In contrast, Darcy velocity and possible tracer pathways identified by tracer experiments cannot be identified uniquely based on SP data.

Alternatively, stochastic inversion is done based on data recorded in deviated wells distributed around the production and injection wells. In this case, principal fluid pathways and permeability magnitudes are reproduced by stochastic inversion of the SP data. The results are comparable to results obtained by tracer experiments. Joint inversion of tracer and SP data yields the best results in terms of small estimation mismatch. Permeability and pathway geometry can be adequately estimated even for an incorrect coupling coefficient as long as it does not differ more than half an order of magnitude from the true value.

1. Introduction

Enhanced geothermal systems (EGSs) are currently being installed and tested for electricity production from geothermal resources even in regions without natural steam reservoirs. In an EGS, the host rock is used as a heat exchanger where pathways are created by hydraulic or chemical stimulation. Hydraulic fracturing consists of injecting water under high pressure into the subsurface in order to increase the pore pressure within the rock mass. This results in fracturing or opening of pre-existing fractures. If the rock is under shear stress, one face of the fracture will dilate relative to the other, preventing the fracture to close again after pressure shut-down. As a consequence, either a fracture network or a single fracture develops, yielding an enhanced permeability which supports increased circulation between suitably placed geothermal wells. In addition, chemical stimulation can be performed by injecting acids into the fracture system, dissolving minerals and hence increasing permeability further.

We aim to quantify distributions of hydraulic properties and the resulting fluid pathways in EGS reservoirs. Information on permeable fluid pathways is essential to predict transient pressure and temperature variation of the operated geothermal reservoir which control the output of thermal power of the EGS. In particular, we study the capability of streaming-potential data to improve the estimation of permeability in fractured geothermal systems. To this end, we study a tracer experiment performed at the Enhanced Geothermal System at Soultz-sous-Forêts (Gérard et al., 2006), France in 2005, as well as a similar synthetic reservoir. The EGS is located in the Lower Rhine Graben. Here, at approximately 5000 m depth, an engineered reservoir was created between 2000 and 2007.

The geologic conditions at Soultz-sous-Forêts are described in Cloetingh et al. (2006). There, three major boreholes GPK2, GKP3, and GPK4 were drilled between 1987 and 2004. They penetrate the sedimentary cover and reach the granitic basement. The boreholes GPK2 and GPK3 intersect a pre-existing fault at a depth of

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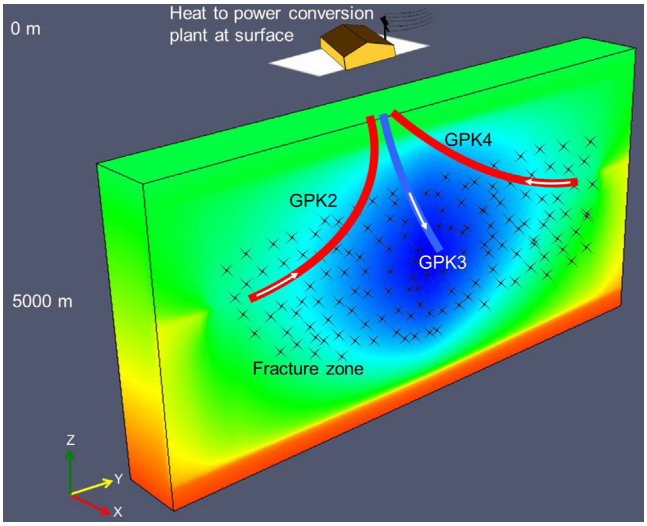

Fig. 1. Simplified scheme of the EGS at Soultz showing the fractures zone, a cooling front (not symmetric in reality), and the injection well (GPK3) as well as the production wells (GPK2, GPK4).

approximately 4700 m, while GPK4 misses the fault. This fault dips approximately 80° striking to 255° N (Gessner et al., 2009).

At Soultz, a tracer circulation test was performed in 2005 for studying the hydraulic connectivity between injection borehole GPK3 and the two production boreholes GPK2 and GPK4 (see Fig. 1). A first interpretation of the tracer experiment of 2005 was suggested by Sanjuan et al. (2006) based on an analytic model, which fitted the first 20 days of the measurement and assumes three possible circulation loops for the tracer within the reservoir. The full 150 days of the curve at GPK3 were modeled by Kosack et al. (2010) who performed a gradient-based deterministic Bayesian inversion to estimate hydraulic parameters in a simplified 3D model.

Based on the results of Kosack et al. (2010), Vogt et al. (2012a,b) performed stochastic inversion approaches in 3D to estimate the heterogeneous permeability and porosity distributions at Soultz in an equivalent porous medium approach. In order to address non-uniqueness of the possible pathways in the reservoir at Soultz, Vogt et al. (2012a) studied a reservoir in which no specific structure or distribution of permeability was fixed beforehand. They identified fitting realizations of a Monte Carlo approach with respect to the GPK2 tracer curve. This results in different alternative distributions of heterogeneous permeabilities. They identified three different possible groups of pathway configurations and corresponding hydraulic properties. Using the Ensemble Kalman Fitler (Evensen, 2003), Vogt et al. (2012b) estimated permeability by numerically updating an ensemble of heterogeneous Monte Carlo reservoir models. Here, tracer curves recorded within GPK2 and GPK4 were fitted simultaneously. As an advantage, this approach also quantifies heterogeneously distributed uncertainty. Alternative approaches for interpreting the tracer test can be found in Blumenthal (2007), Gentier et al. (2013), Held (2011) and Radilla et al. (2012)

Finsterle et al. (2013) proposed the use of microhole arrays to deal with heterogeneous permeability and flow channels in an EGS which has characteristics similar to the reservoir at Soultz. They make use of the fact that microholes are less expensive than standard wells. In case of a microhole array for production and injection, most of the heat exchange takes place within the wells itself.

This study is a follow up study of Vogt et al. (2012a,b). Here, we simulate whether including hypothetical streaming-potential (SP) data during the stochastic inversion could improve the knowledge of the hydraulic reservoir properties. Conditioning of the ensemble to SP data may also decrease non-uniqueness and uncertainty. During the actual tracer test, no SP data were recorded. Therefore, this study is synthetic.

Nevertheless, streaming potential (or self potential) has previously been used to monitor fluid flow in geothermal reservoirs (Corwin and Hoover, 1979; Ishido and Mizutani, 1981; Sill, 1983). For instance, SP measurements have been used to monitor fluid injection for hydro-fracturing the geothermal reservoir at Soultz-sous-Forêts (Darnet et al., 2006). Here, fluid injection in 5000 m depth caused a SP signal of a few mV at the surface in spite of the large depth, probably due to the high conductive metal casing of the injection well. SP application to geothermal systems has also been reported by Revil et al. (1999). Ishido and Pritchett (1999) modeled SP associated with subsurface fluid flow numerically. Simulations of hydrothermal systems were also performed by Yasukawa et al. (2003) using SP survey results. Sheffer and Oldenburg (2007) investigated SP signals in groundwater models at the field scale.

Inversion of SP data to estimate hydraulic conductivity has been performed by e.g. Malama et al. (2008). Minsley (2007) and Minsley et al. (2007) reported on numerical modeling and inversion of SP data. Jardani and Revil (2009) performed stochastic inversions and found that a permeability estimate of a hydro-thermal system is obtained accurately only if SP data at the surface and temperature data within wells are jointly inverted. In a laboratory experiment, Ikard et al. (2012) identified preferential flow paths using the SP signal caused by a salt tracer. They also estimated permeability and porosity of preferential flow paths by Markov-chain Monte Carlo sampling in a synthetic case study. Soueid Ahmed et al. (2013) developed a code for 2D forward and inverse streaming-potential simulations and applied it on different synthetic scenarios. They showed that the electric current density could be estimated successfully based on SP data at the model's surface using their code.

Stimulation events and associated flow paths can be monitored by transient SP recording, as reported by Mahardika et al. (2012) and Haas et al. (2013).

In this paper, we study the potential use of SP monitoring data for the characterization of the permeability distribution in EGS reservoirs. This paper is organized as follows: the basic equations describing fluid flow, tracer transport, and streaming potential as well as stochastic inversion tools are introduced in Section 2. In Section 3, we investigate whether different equally likely flow paths at Soultz found by Vogt et al. (2012a) can be uniquely identified using SP data. In the next step, we study whether considering SP signals in stochastic parameter estimation based on the Ensemble Kalman Filter (EnKF) technique similar to Vogt et al. (2012b) improves permeability estimates (Section 4). Finally, we conclude our findings (Section 5).

2. Theoretical background

2.1. Hydrodynamics

Fluid flow through a porous medium is commonly described by Darcy's law:

$$\boldsymbol{v} = -\frac{\rho_f g \boldsymbol{k}}{\mu_f}(\nabla h + \rho_r \nabla z), \quad (1)$$

where $\boldsymbol{v}$ is the specific discharge (or Darcy velocity) ($m^3\,m^{-2}\,s^{-1}$), $\boldsymbol{k}$ the hydraulic permeability tensor (m^2), μ_f the fluid dynamic viscosity (Pa s), ρ_f fluid density ($kg\,m^{-3}$), g gravity ($m\,s^{-2}$), h the hydraulic head h (m), and z is the vertical position (m) pointing positive upwards. ρ_r is defined by $\rho_r = (\rho_f - \rho_0)/\rho_0$, where ρ_0 is density at reference conditions (i.e. temperature).