# Numerical analysis and visualization of uncertainty effects in thermo-hydro-mechanical coupled processes in a hot-dry-rock geothermal reservoir

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**Abstract** We present an uncertainty analysis of thermo-hydro-mechanical (THM) coupled processes in a typical hot-dry-rock reservoir in crystalline rock. The conceptual model is an equivalent porous media approach which is adequate for available data from the Urach Spa and Falkenberg sites (Germany). The finite element method (FEM) is used for the numerical analysis of fully coupled THM processes, including thermal water flow, advective-diffusive heat transport, and thermo-poro-elasticity. Reservoir parameters are considered as spatial random variables and their realizations are generated using conditional Gaussian simulation. The results show the influence of parameter ranges on the reservoir evolution during long-term heat extraction taking into account fully coupled THM processes. We found that the most significant factors are permeability and heat capacity variations. The study demonstrates the importance of taking parameter uncertainties into account for geothermal reservoir evaluation in order to assess the predictability of numerical modelling.

**Key words** hot-dry-rock geothermal reservoir; uncertainty analysis; thermo-hydro-mechanical coupled processes; Monte-Carlo simulation; visualization

## INTRODUCTION

Data uncertainty is one of the major problems in subsurface reservoir analysis. Direct borehole measurements are very limited due to technical issues and costs. Normally data are available from core samples and well-bore logging for the local scale and from geophysical measurements (e.g. microseismic monitoring) for a larger scale. Thus, subsurface models are derived from limited information and include uncertainties. For hot-dry-rock (HDR) geothermal systems, aspects of uncertainty have been investigated in the framework of sensitivity analysis and parameters identification so far. Fractal and statistical Discrete Fracture Network (DFN) models have been developed, e.g. by Tezuka & Watanabe (2000). Inversion methods have been used to identify physical rock parameters in order to reproduce the observed reservoir behaviour (Lehmann *et al.*, 1998). Monte-Carlo analysis is one common method for quantifying parameter uncertainty and the corresponding system evolution. Using geostatistical techniques enables the generation of multiple stochastically equivalent realizations which take into account the status of the incomplete knowledge. Before starting stochastic simulations, assumptions concerning parameter distribution, e.g. histogram, spatial correlation, correlation with other parameters, have to be decided. Usually those assumptions are determined from site observation data. However, little information about histogram and variogram analysis for deep crystalline rocks is available in the literature. The plan of this work is to develop a methodology for uncertainty analysis of thermo-hydro-mechanical (THM) coupled processes in deep geothermal systems during massive heat extraction.

### Statistical approach

The present statistical approach to the uncertainty analysis consists of three parts: (1) determin-ation of statistical models for parameter distributions, (2) stochastic realizations of parameter fields using conditional Gaussian simulation based on the defined stochastic models, and (3) Monte-

Carlo analysis with numerical simulation of fully coupled THM processes using randomly generalized multiple parameter distributions. As basic assumptions of the stochastic model, we consider parameters of thermal, hydraulic and mechanical processes as spatial random variables. Parameter distributions have spatial correlation as well as heterogeneity over the reservoir. As the parameters in principle can be measured in the borehole (i.e. from cores), the parameter values are assumed to be known along the boreholes. The stochastic properties of the random field are given by the probability distribution and spatial correlation (variogram).

At the current stage and to demonstrate the methodology, we make additional simplifying assumptions. Probability distributions can be determined from measurements if frequency distributions of the parameters are available. As we can rely only on minimum/maximum values for the parameters and the statistical properties are not known very well, we use the simplest case: normal distributions. The shape of parameter distributions is determined from the parameter range given by site measurements or in the literature. For a variogram model, we use the spherical model for all parameters because of the simple linearity. Furthermore, we assume that parameters do not have correlation to each other so that spatial distributions of each parameter are determined individually, although a number of authors have investigated the coupling between parameter relationships such as relationships of permeability and porosity as well as porosity and rock heat conductivity (Pape *et al.*, 1999; Surma & Geraud, 2003).

## APPLICATION

The application demonstrates the methodology for an uncertainty analysis of THM coupled processes in a typical geothermal reservoir in crystalline rock. The analysed parameters are *T* (rock heat conductivity, rock specific heat capacity), *H* (permeability, porosity), *M* (Young's modulus, Poisson ratio). The study is based on a data set for the German Hot-Dry-Rock projects at Urach Spa (Haenel, 1982) and that has been complemented with additional data from other crystalline reservoirs such as Soultz-sous-Forêts (Huenges, 2010). We use a finite element model OpenGeoSys which takes into account fully coupled THM processes (Wang *et al.*, 2009; www.opengeosys.net).

### Methodology of uncertainty analysis

The uncertainty analysis is conducted in two steps. First, using a relatively small number of realizations for our Monte-Carlo simulation (10), we "screen" the variability effect of the THM parameters on the long-term reservoir behaviour as well as examining the importance of different statistical distributions. We compare the results for a homogeneous reservoir using minimum and maximum values of the parameter range and a smaller number of realizations (10) using the stochastic model. The remaining reservoir parameters correspond to mean values. Second, for the most sensitive parameters we conduct a Monte-Carlo simulation with a large number of realizations (100) to provide statistically representative results. The reason for this two step procedure is the enormous computational expense of using the 3-D fully coupled THM numerical simulations. In addition, we use high-performance-computing to run the parallelized version of the THM model (Wang *et al.*, 2009; Watanabe *et al.*, 2009) and conduct each Monte-Carlo simulation in a parallel way.

### Numerical model

The geothermal reservoir is located at between 3850 and 4150 m depth. The proposed boreholes for a dipole flow circulation system are located 400 m apart. The hydraulically active areas allow the reservoir to be represented geometrically as a cuboid 300 m high, 300 m wide and 800 m long (Fig. 1). The temperature of the reservoir is around 160°C and varies with the depth. Fluid injection temperature is assumed to be 50°C. The injection well is considered to have an overpressure of 10 MPa and the production well an underpressure of 10 MPa. The reservoir structure is represented with an equivalent porous medium approach as there is not sufficient data available in order to justify a discrete fracture network model. The equivalent porous medium approach corresponds to highly fractured reservoirs. Physical processes are the thermal water flow, advective-diffusive heat transport, and thermo-poro-elasticity. Material properties of geothermal fluids are nonlinear functions of salinity, temperature and pressure (McDermott *et al.*, 2006). The details of the numerical model can be found in Watanabe *et al.* (2010).

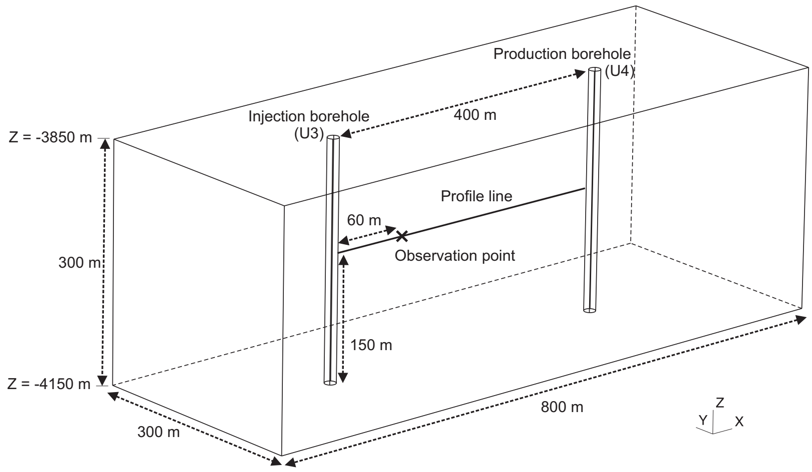


**Fig. 1** Reservoir model with a borehole doublet.

### Stochastic model for reservoir parameterization

The statistical parameters of rock properties we used are summarized in Table 1. The probability distributions correspond to the normal distribution and variogram models with spherical shape. The range of the variogram model is 50 m. The sill is identical to the sample variance. Nugget effects are not considered. For the following sensitivity analysis, we assume that the permeability histogram follows the Gaussian distribution shown as logarithm with base 10. The permeability values vary from $10^{-17}$ m$^2$ to $10^{-15}$ m$^2$ corresponding to the laboratory measurement and stimulated reservoir permeability in Urach, respectively (McDermott *et al.*, 2006).

**Table 1** Assigned statistical properties for the HDR geothermal reservoir.

| Parameter | Symbol | Mean | Unit | Std |
|---|---|---|---|---|
| Permeability (logarithm with base 10) | $\log 10(k)$ | −15.738 | (m$^2$ ) | 0.3077 |
| Undisturbed permeability | $k$ | $21.8 \times 10^{-18}$ | m$^2$ | $7.17 \times 10^{-18}$ |
| Porosity | $n$ | $4.05 \times 10^{-3}$ | - | $8.2 \times 10^{-4}$ |
| Rock heat conductivity | $\lambda^s$ | 2.79 | W/(m K) | 0.08 |
| Rock specific heat capacity | $c_p^s$ | 850 | J/(kg K) | 55.5 |
| Young's modulus | $E$ | 64 | GPa | 0.8 |
| Poisson ratio | $\nu$ | 0.225 | - | 0.08 |

## RESULTS AND DISCUSSION

### Sensitivity analysis

Sensitivity analysis was conducted to assess the importance of the individual THM parameters on the thermal reservoir evolution. Results for two important properties are shown in Fig 2(a) and (b), i.e. rock specific heat capacity and permeability, respectively. It can be seen that the permeability, ranging from values for undisturbed $k = 10^{-17}$ m$^2$ and stimulated areas $k = 10^{-15}$ m$^2$ is clearly the most important parameter. Next to permeability, rock specific heat capacity representing heat

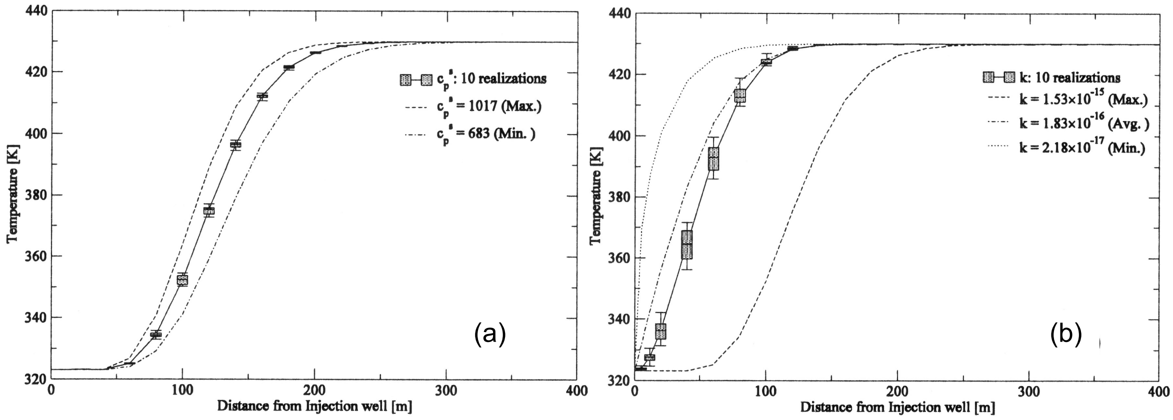


**Fig. 2** (a) Sensitivity of rock specific heat capacity, and (b) sensitivity of permeability.

storage effects, is the second most important parameter. The variances of mechanical (*M*) parameters, porosity, Young's modulus and Poisson ratio are of less importance under the given assumptions. As expected, all stochastic simulation results are captured by enveloping curves produced with the minimum and maximum parameter values, respectively. Interesting is the fact that the min/max values put strong bounds to the stochastic results. As this needs to be elaborated more, the uncertainty of reservoir permeability is investigated in a more detailed Monte-Carlo analysis. Actually, assuming an overall maximum value for permeability means a completely stimulated reservoir.

## MONTE-CARLO ANALYSIS

The Monte-Carlo analysis was conducted for permeability after the above sensitivity analysis. To make the reservoir model more realistic, the permeability increase as a result of the massive hydraulic stimulation is assumed to be dependent on the borehole distance as proposed by Baisch *et al.* (2004). We consider a reservoir type, where hydraulic stimulation is conducted in two boreholes with a quadratic permeability enhancement factor and the porosity–permeability relationship corresponds to that from the Falkenberg site (Watanabe *et al.*, 2010). To perform a representative Monte-Carlo simulation we conduct 100 stochastic simulations.

Results of the analysis are shown by means of envelope curves and variances. Figure 3 illustrates the 20%, 80% and 100% uncertainty zones of the 100 temperature profiles between the boreholes after 15 years. The 20% zone covers 20% of the 100 temperatures obtained around the median. The 100% zone provides an envelope to all 100 realizations with a maximum temperature

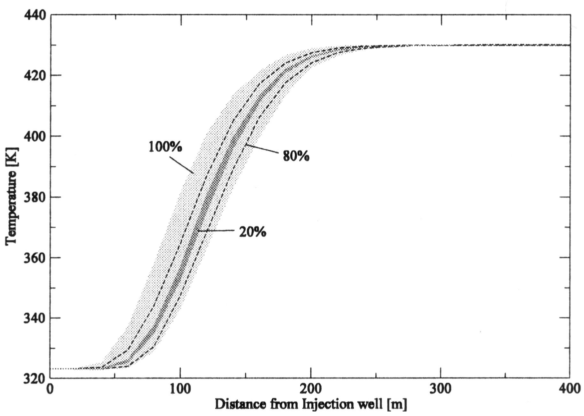


**Fig. 3** Temperature frequencies at the observation point.

difference of about 40 K. The maximum standard deviation is found to be around 8 K. The figure also shows that the uncertainty, i.e. variance, is largest at places where temperature gradients are highest, i.e. around the propagating cooling front. This is because the uncertainty of permeability is deeply related to the flow field in the reservoir and consequently affects the heat transport process which is mainly by forced convection. The region near the injection borehole is almost cooled down after 15 years in all realizations and the variance of temperature is nearly zero. Therefore, the effects of permeability uncertainty on thermal evolution appeared mostly near the propagation front. Figure 4 shows a first 3-D visualization of THM processes including uncertainty with path lines of water flow, temperature isosurfaces, and standard deviations of temperature distributions. Higher uncertain zones are highlighted by darker colour. Thus the 3-D visualization can clearly indicate within which volume the isosurface will lie with a certain confidence. For more details please refer to Zehner *et al*. (2010). The related Monte-Carlo analysis of the coupled THM problem is computationally very expensive. To enhance computational efficiency, the parallel FEM based on domain decomposition technology using message passing interface (MPI) is utilized to conduct the numerous simulations. All 100 Monte-Carlo simulations were finished within two days using 80 CPUs instead of the three months which would have been necessary on a single CPU computer.

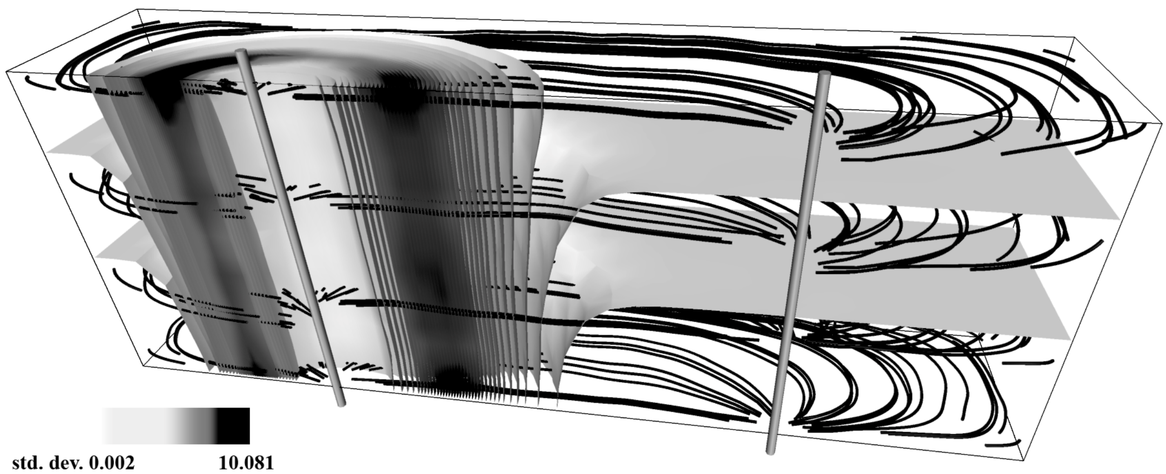


**Fig. 4** Visualization of uncertain THM processes in a geothermal reservoir. Plotted are flow path lines, temperature isosurfaces and standard deviations as a result of 100 Monte Carlo simulations. A colour legend shown in the figure is for the standard deviations.

## CONCLUSION AND OUTLOOK

Using a combination of the fully coupled numerical THM model and the classical Monte-Carlo simulation, we present an uncertainty analysis of T-H-M parameters on the long-term geothermal reservoir evolution using high-performance-computing. The sensitivity analysis shows that permeability and rock specific heat capacity are the most important reservoir parameters. Less relevant is rock heat conductivity. As a result of the stochastic THM analysis, we found a maximum temperature uncertainty range of about 40 K after 15 years of reservoir exploitation (Fig. 4). Despite the achievements, the stochastic THM concept has to be further developed in future work. Due to the limited available information, it is difficult to obtain statistical properties of geothermal HDR reservoirs. This is a typical situation for deep geological reservoirs where little data are available. This situation makes uncertainty analysis questionable and at the same time important as it is the only way to assess the uncertainty of reservoir evolution.

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