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Stochastic Estimates of the Permeability Field of the Soultz-sous-Forêts Geothermal Reservoir – Comparison of Bayesian Inversion, MC Geostatistics, and EnKF Assimilation

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The knowledge of the permeability distribution at depth is of primary concern for any geothermal reservoir engineering. However, permeability might change over orders of magnitude even for a single rock type and is additionally controlled by tectonic or engineered fracturing of the rocks. During reservoir exploration pumping tests are regularly performed where tracer marked water is pumped in one borehole and retrieved at one or a few others. At the European Enhanced Geothermal System (EGS) test site at Soultz-sous-Forêts three wells had been drilled in the granitic bedrock down to 4 to 5 km and were hydraulically stimulated to enhance the hydraulic connectivity between the wells. In July 2005, a tracer circulation test was carried out in order to estimate the changes of the hydraulic properties. Therefore a tracer was injected into the well GPK3 for 19 hours at a rate of 0.015 $m^3\,s^{-1}$ and a concentration of 0.389 $mol\,m^{-3}$. Tracer concentration was measured in the production wells over the following 5 months, while the produced water was re-injected into GPK3. This experiment demonstrated a good hydraulic connection between GPK3 and one of the production wells, GPK2, while a very low connectivity was observed in the other one, GPK4. We tested three different approaches simulating the pumping experiment with the numerical simulator shemat_suite in a simplified 3D model of the site in order to study their respective potential to estimate a reliable permeability distribution for the Soultz reservoir: A full-physics gradient-based Bayesian inversion, a massive Monte Carlo approach with geostatistic analysis, and an Ensemble-Kalman-Filter (EnKF) assimilation. A common feature in all models is a high permeability zone which acts as main flow area and transports most of the tracer. It is assumed to be associated with the fault zone cutting through the boreholes GPK2 and GPK3. With the Bayesian Inversion we were able to estimate a parameter set consisting of porosity, permeability, and dispersivity which produces a nearly perfect fit to the measured tracer data. The models used for the inversion are simplified to the main geologic elements of the geothermal reservoir and consist of only 2 to 4 regions of constant properties. Optimal a-posteriori parameter estimates will be complemented by an analysis of parameter dependencies and uncertainties as a by-product of the nonlinear inversion. With both ensemble methods a cell-wise discrete spatial distribution of the permeability can be retrieved. For MC approach we produced a large number of system realizations with permeability distributions randomly picked from a bimodal histogram of the enhanced zone and the surrounding. The main fracture area is modelled by assuming a high permeability and an anisotropic correlation length. After forward simulation of the tracer experiment, the successful realizations are selected and further grouped to study principal features of the permeability distribution. Similar to the MC approach, the EnKF is based on a forward propagation of an ensemble of realizations. At successive instants in time, different kinds of data as tracer concentration, bottom hole pressure, and permeability in various drill holes are collected in one data vector and used to update (assimilate) the system variables to improve the match between observation and simulation leading to a convergence of the ensemble. We studied the performance and spatial resolution of the EnKF procedure for a 3D test model which is based on the borehole locations and tracer experiment of the Soultz geothermal reservoir. We used all available information to condition the pressure field and to estimate the permeability. Already after a few assimilation steps the ensemble average permeability shows coarse features of the expected permeability field. However, any estimates of smaller scale permeability variations turn out to be very sensitive to the (potentially unknown) correlation lengths.