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MeProRisk – a Tool Box for Evaluating and Reducing Risks in Exploration, Development, and Operation of Geothermal Reservoirs

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ABSTRACT

In developing geothermal resources there is a high risk of failure compared to hydrocarbon exploration. The MeProRisk projects aims at improving the strategies in all phases of the reservoir life cycle. It is a joint enterprise of three German universities and two companies: RWTH Aachen; FU Berlin; University of Kiel; Geophysica GmbH (Aachen); and RWE Dea AG (Hamburg). It is funded for three years by the German Ministry of Education and Science (BMBF).

The key idea of this project is to understand the development of a given reservoir as an iterative process. Starting from existing geological information and geophysical data, one or more conceptual models will emerge which will be used for first numerical simulation, forward and inverse. The models will be progressively refined by including reliable rock properties based on a statistical analysis and geological fine structure deduced from sophisticated seismic interpretation. The use of inverse simulation techniques in a broad sense will not only finally yield an optimal model but provide estimates of uncertainty and resolution for the model. This information is useful for further optimizations of experiments, not the least important of which is comprised of choosing the locations of new exploration wells.

1. INTRODUCTION

Geothermal reservoirs are a safe and environmentally friendly way of producing energy in times of increasing shortage of hydrocarbon resources.

While geothermal energy is used routinely for local heating, the exploitation of deep geothermal fields for electrical power generation still poses high challenges. This is at least partly due to the economic and technical risk of failure during various phases of development of geothermal fields compared to hydrocarbon exploration.

Generation of electrical power from geothermal reservoirs requires the drilling of deep boreholes (< 3 km) for water injection and production. While the temperature in the injection and production boreholes is well known, the amount of recycled water, and thus the produced amount of heat, depends strongly on the far-reaching water circulation in the rock at depth.

Thus, better a-priori information about the expected water circulation field will reduce the risk for geothermal exploration. Realistic numerical simulations of heat transport due to water circulation require detailed information on the distribution of different types of rock at depth, their physical properties, and the geological structure in the deeper basement.

The basic idea in this project lies in viewing the development of a given geothermal reservoir as an iterative process. Initially only very limited information exists for any new reservoir, e.g. surface heat flux and geology; the simulation of water circulation involves large uncertainties and, correspondingly, the economic risk is high. At a later stage of reservoir development, the numerical models will be updated continuously as new information becomes available from surface measurements or borehole experiments. Once first wells have been drilled, the character of experiment shifts from static exploration to dynamic interaction with the reservoir, such as injection experiments and their monitoring. This data will be used to increase information on the deeper basement structure and rock properties as permeability or thermal conductivity which allows refinements of the flow simulation. The process results from forward and inverse flow simulations used help to define areas of large uncertainties as well as to optimize further exploration, thus reducing the economic risk. This concept is illustrated in Fig. 1, where the blue iteration loop may be a characteristic for the exploration and early exploitation phase, while the green one will become increasingly important in the later exploitation and production phase.

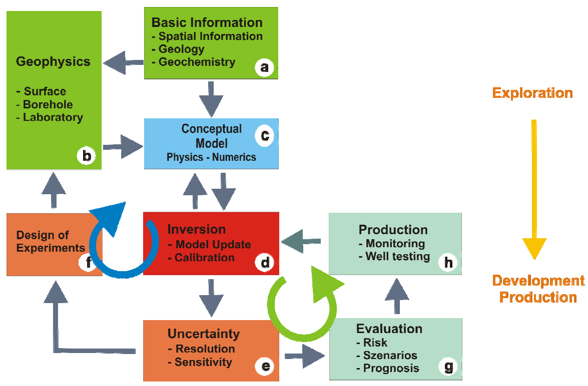

Figure 1: Principle concept of MeProRisk: the blue iteration loop is for the exploration and early exploitation phase and the green one for the later exploitation and production.

The use of all of this information by one simulation tool poses a great challenge. Inverse problems require orders of magnitude more computing resources, and the development of appropriate theoretical and numerical methods for their use is one of this project's primary aims. Due to the often subtle signatures of geothermally relevant exploration targets, it is also necessary to improve experimental techniques for setting up and updating the model by developing new and improved methods. This comprises, for instance, developing methods for estimating hydraulic and thermal properties from geophysical observations (e. g. electric,

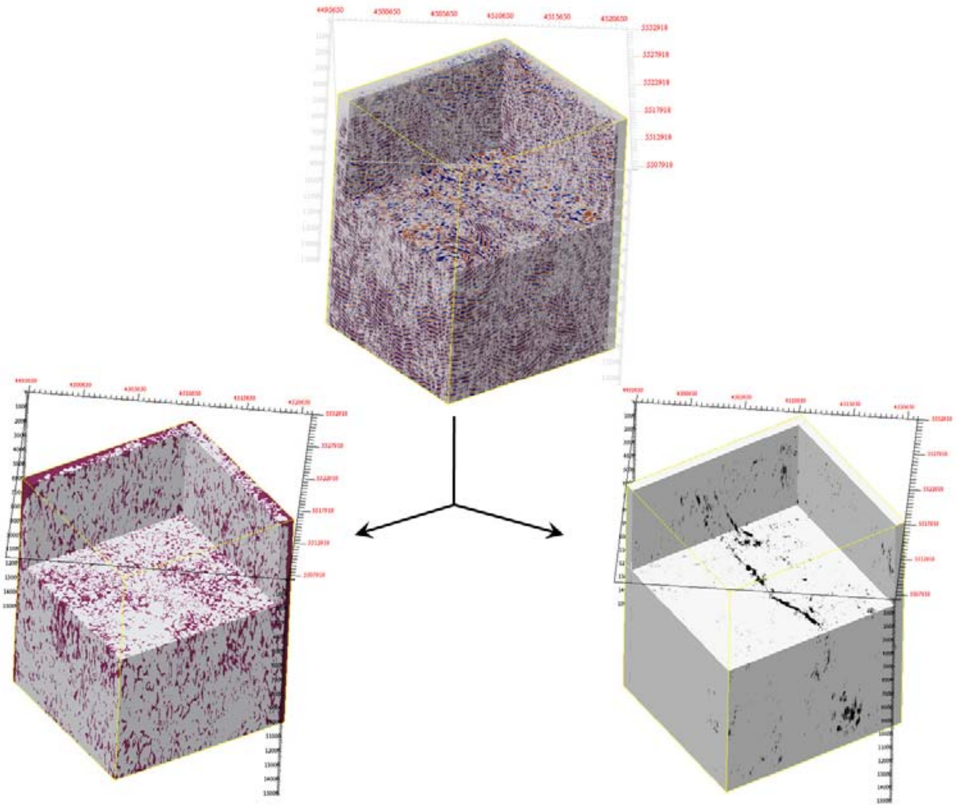

Figure 2: Original depth-migrated data (top) of a 3D seismic experiment, smaller scale fracture zones (left), major fracture zones (right)

seismic, and micro-seismological) and for characterizing natural or engineered fracture zones.

The broad target of this project requires expertise in various fields of science. The geological structure of a reservoir is determined from interpretations of 3 D seismic data and borehole logs. New interpretation methods are developed within the scope of the project to determine small interconnected fracture systems, which are important for water transport. Petrophysical rock properties are compiled from measurements on core samples, inversion of borehole seismic observations and log interpretation, and statistically studied on a large data set to reliably estimate rock parameters. Reservoir simulation is performed with a new, sophisticated numerical tool (SHEMAT-suite; Rath et al., 2006) which is composed of the efforts of specialists in fluid dynamics and inversion theory, scientific computation and parallelization, and 3D visualization. This contribution presents first achievements with respect to all of these fields.

2. THE MEPRORISK TEAM

The key activities in the MeProRisk project are distributed among six working teams at three universities (RWTH Aachen, FU Berlin, University of Kiel), a geophysical consulting company (Geophysica GmbH, Aachen) and an industrial partner (RWE Dea, Hamburg)

The Institute of Applied Geophysics and Geothermal Energy (RWTH Aachen) stands for the numerical simulations and experimental design; the Institute of Scientific Computing (RWTH Aachen) contributes with new methods of numerical parallelization, algorithms for solving partial differential equations with automatic differentiation (Bischof et al., 2008) and 3D visualization; the Institute of Applied Geophysics (University of Kiel) deals with interpretation of 3D seismic data to automatically detect fractured zones in a reservoir; the Institute of Geophysics, (FU Berlin) studies micro-earthquakes to provide in situ estimates of the permeability tensor characteristics, the Geophysica GmbH (Aachen) focus on inferring geothermally relevant petrophysical input parameters from borehole, core and cutting data; and RWE Dea AG (Hamburg) provides borehole and seismic data from two former hydrocarbon production fields.

Here we shortly describe the work of the various MeProRisk team partners in the framework of a hypothetical geothermal reservoir.

2.1 Establishing a geological reservoir model with petrophysical rock properties

The first exploration step to develop a potential geothermal field consists in drilling one or several boreholes, making measurements with geophysical logs and retrieving drilling cuttings and cores. This data is used by Geophysica GmbH to establish the thermal gradient with depth, to identify the geological stratigraphy and to determine petrophysical properties. Standard log interpretation procedures (Doveton and Cable, 1979) can be used to determine the lithological composition and determine rock porosity. A rough estimate of thermal conductivity can be obtained from compilations

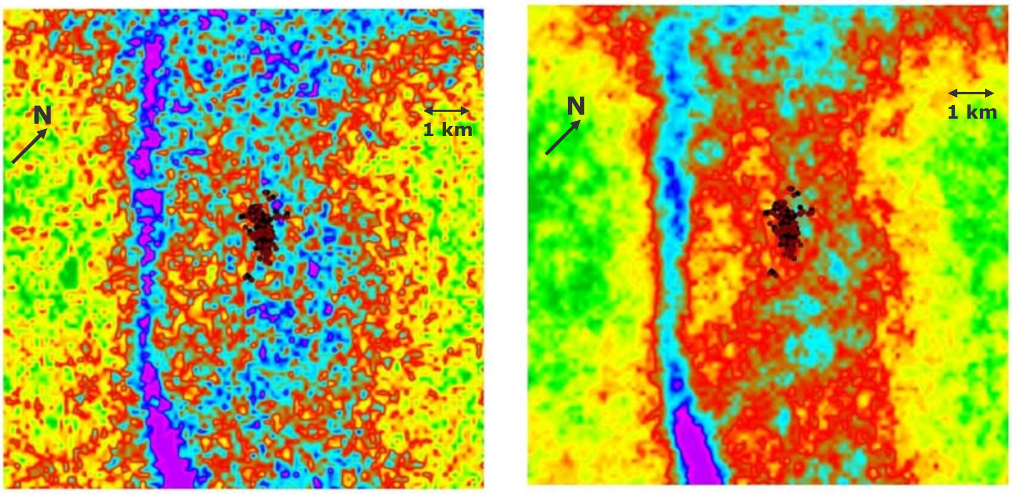

Figure 3: The original data (left side) and image resulting from attribute processing (right side) shown for an image slice at 3500 m depth. Circles denote locations of induced micro-seismic

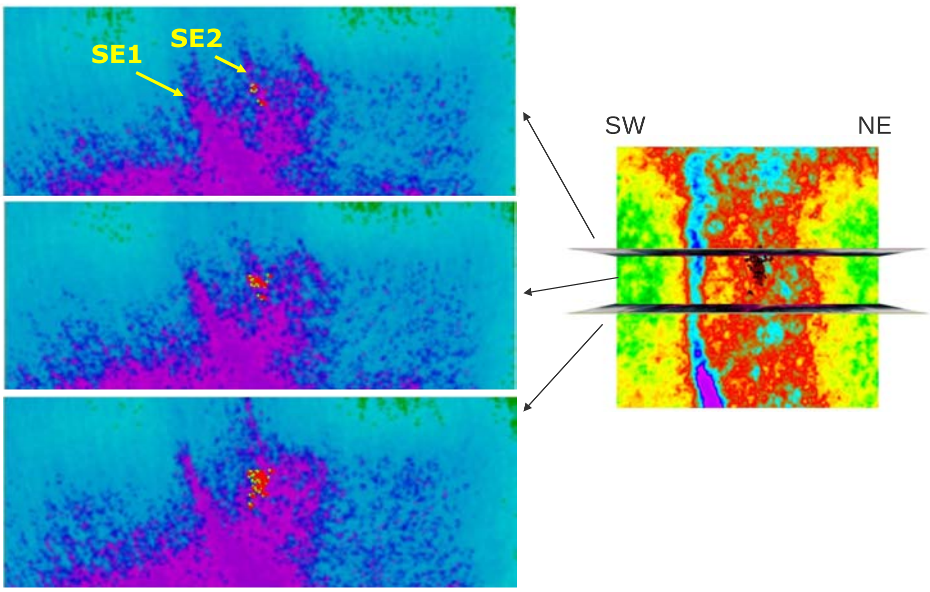

Figure 4: Vertical slices at several lateral positions. Note that the view direction is from NW to SE

of thermal rock properties (e.g. Čermák and Rybach, 1982; Clauser and Huenges, 1995; Clauser, 2006).

Using appropriate software to combine these data sets (e.g. GoCad, *Schlumberger* Petrel) allows establishment of an initial structural model of the reservoir geometry including first estimates of hydraulic and thermal properties. However, the ranges of these rock properties for various rock types are too large to be a useful constraint of these properties in a geothermal target reservoir.

To improve this situation, a large data set of rock properties has been compiled to constrain robustly the hydraulic and thermal properties of rocks. Further, for a rock sample collection which represents the relevant stratigraphy of the geothermal reservoir, the thermal conductivity is measured on these samples in the laboratory.

From the known volume fractions of the N different rock types, continuous profiles of thermal conductivity λ can be calculated from an appropriate mixing law (e. g. the geometric mean).

$$\lambda = \prod_{i=1}^{N} \lambda_i^{k_i} \qquad (1)$$

This data is analyzed statistically, to obtain information on the uncertainty of the determined properties for the different rock types. This part of the project will provide a structural model of the target area including well constrained estimates of hydraulic and thermal properties.

2.2 Integrating seismic data – detection of fault systems

If an array of seismic data of an exploration field is available, straightforward depth migrations are performed routinely to resolve subsurface structures. However, fracture zones and strongly inclined faults are difficult to recognize in their geometrical shape. On the other hand, sub-vertical fracture zones are preferred pathways for circulating water. For a successful reservoir simulation it is essential to account for them correctly.

Members of the Institute of Geophysics (University of Kiel) are developing new methods using 3D seismic data for an automatic detection of fracture zones in the first step of the quantitative seismic interpretation scheme.

First test results using data from the southern German crystalline (KTB ("Continental Deep Drilling"); Emmermann und Lauterjung, 1997) and from Permo-Triassic sediments of the North German Basin indicate that the method can be successfully applied when adopted to the geological setting.

The major fault systems can be identified clearly in the frequency-wavenumber-spectra. Therefore, a frequency-wavenumber-filter was designed and applied to the data which isolates these major fault systems. The result can be further enhanced by computing seismic trace envelopes. Smaller scale fracture zones can be detected by an anisotropic log-Gabor filter (Field, 1987) which yields directional frequency information depending on a prescribed rotation (see Fig 2). In the case of sediments from the North German Basin good results have been achieved with eigenstructure-based coherency calculations (Gerstzenkorn and Marfurt, 1999). In particular, fractures are very well seen in time slices.

Furthermore, at the Institute of Geophysics (FU Berlin), a tool has been developed using seismic attributes (Jaya, et al., 2009) to enhance seismic reflectivity which is able to resolve geological features which could not be detected in the original migrated seismic data. This tool has been applied to 3-D Kirchhoff pre-stack depth migrated data from the KTB drilling site (Buske, 1999). The interpretation of fault geometries associated with micro-seismic events proved to be more feasible using seismic attributes. The comparison between the original data and the result of successive attribute processing (median filter and energy attribute) is shown in Fig. 3. In this figure improvements and enhancements associated to the fault continuity, structural features and subtle amplitudes can be observed. In Fig. 4, features of particular interest are two dominant fault systems encountered at about 7.2 and 4.0 km depths. Both, the SE1 and SE2 faults, are more visible when using seismic attributes. In addition, a complex fault system elongating in the South-North direction is also visible and probably constitutes the regional tectonics.

2.3 Retrieving hydraulic properties from micro-earthquakes

Apart from resolving geometrical structures of the target reservoir, seismic methods can also be employed to estimate hydraulic properties of reservoir rocks. At some stage in reservoir development fluid injection experiments are commonly performed. Injection of fluids in the rock matrix is mostly accompanied by the occurrence of micro-earthquakes which can be monitored by borehole and surface seismometers. (The process of fluid injection for the Soultz-sous-Forêts hydrothermal field (France) is described in detail in Sanjuan et al., 2006). The precise location of these micro-seismic signals allows generating a high resolution image of hydraulically activated fault systems in reservoirs (Rowe et al., 2002). The micro-seismic cloud for the Soultz-sous-Forêts hydrothermal field is given in Fig. 5.

Moreover, at the Institute of Geophysics (FU Berlin) new analysis methods of the temporal-spatial distribution of micro earthquake have been developed to estimate material properties of the reservoir, such as hydraulic diffusivity and permeability (Shapiro et al., 2002) on a larger scale (10^2-10^3 m). The idea is based on the assumption that the spatial propagation of hydraulically induced seismicity is caused mainly by the pore pressure relaxation process. Commonly, a positive correlation is observed between regions of high reflectivity and high permeability (Shapiro et al., 2006).

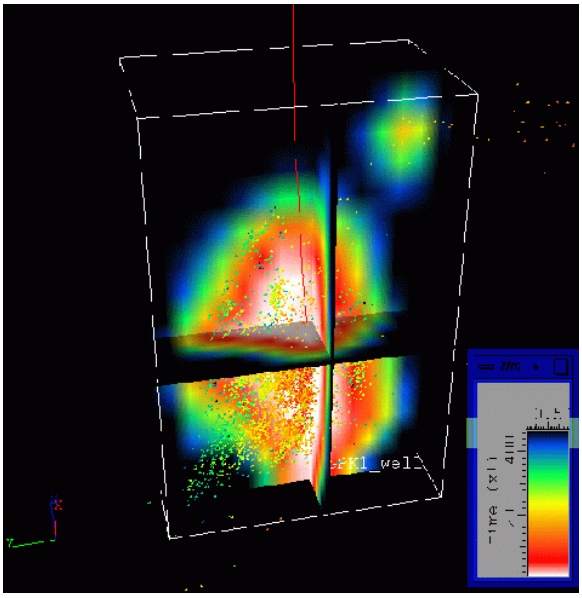

Figure 5: Micro-seismicity cloud of the Soultz-sous-Forêts (France) borehole injection experiment. The red line shows the borehole (GPK1). The injection is located in crystalline rock, approximately at a depth of 3 km. The vertical and horizontal sizes of the shown region are approximately 1 km. The coloured points are micro-seismic events. Colours denote the occurrence times.

Recently, an effort has been made to improve the correlation of seismic reflectivity and micro-seismic events using seismic attributes analysis, in particularly to those related to SE2 fault (Jaya et al., 2009; see Figures 3 and 4). The joint representation of seismic attributes and micro-seismic events has proven to provide further evidence of this correlation.

2.4 Numerical simulation of hydrothermal flow with uncertainty estimates

At various stages of reservoir acquisition, simulation of hydrothermal flow is a tool for directing further investigations iteratively. The environment which we use in this project is SHEMAT_suite (Rath et al., 2006) which cannot only handle the forward but also the inverse problem. Several approaches to the inverse problem are offered by this toolbox. One of these is based on geostatistical simulation (Deutsch and Clayton, 1997). In this case, the tool acts as a Bayesian estimator for the conditional probability of certain model parameters if uncertain data was observed and prior statistical information exists concerning the values of model

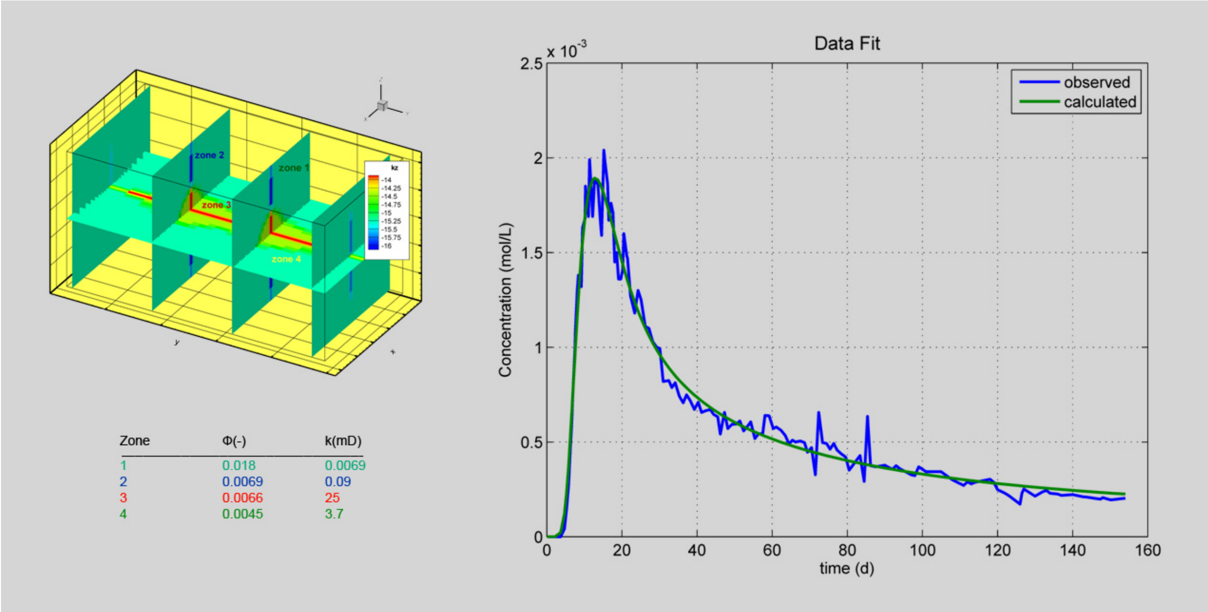

Figure 6: Fit of simulated to observed tracer concentration at the GPK2 borehole at Soultz-sous-Forêts (France) during a test, lasting for 140 days (right). The stimulated zones of the simplified numerical model (left) are color-coded, the values for porosity Φ and permeability k are given in the small table.

parameters and their spatial distribution. A typical application of this program is demonstrated in the contribution by Vogt et al. (2009) to the Proceedings "World Geothermal Congress 2010 Bali, Indonesia". This approach, however, requires considerable computer resources, even when run in a parallelized manner.

Although less general in their application than the stochastic simulations, gradient-based methods may be helpful in practice. Assuming Gaussian statistics, inverse procedures may be used to derive a maximum-a-posteriori (MAP) estimates for a given set of system parameters (rock properties of a geological unit or boundary conditions). To obtain the necessary derivative information, the forward code, which is the core of all implemented methods, is enabled to calculate sensitivities by means of Automatic Differentiation (AD, Berz at al., 1996; Bischof et al., 2008). This allows a fast integration of modifications (e.g., new physics or numerical formulations) into the inverse environment. These new features have been applied to a number of field cases. Here we show the case for the simulations of water injection with tracers for the hydrothermal test area Soultz-sous-Forêts (Rath and Kosack, 2008). A set of simplified conceptual models was used, which all explain the available observations equally well (see Fig. 6). However, it turned out that the parameters describing the models, such as rock properties and geological structure, are not well enough constrained to discriminate between these various models. This emphasizes the need of more and independent data such as time series of borehole temperatures or pressure build-up.

2.5 Scientific visualization of sophisticated 3D time variable arrays

In 3D volume visualization, any type of scalar data is mapped to an optical parameter, such as colour or transparency. This allows a simple, intuitive understanding of complex fields. Interactive calculations make real-time animations possible with large amounts of fluid particles. New algorithms will be applied (Lodha et al., 1996; Djurcilov et al., 2001)) to display uncertainties of data and model parameters, e.g. by adding noise to bias the image. Moreover, visualization is not only used simply to display observed or modelled data. It has also the potential to interactively explore the model space to identify regions of particular interest.

3. OUTLOOK

The innovative aspect of the MeProRisk project lies not only in new methodological developments in various disciplines but in establishing a guideline strategy for successful reservoir exploration and exploitation; the whole is more than the sum of its parts.

In practice, applying this guideline strategy to a target area for geothermal energy production will improve in iterative steps successively the information about reservoir geometry; allows robust estimates of rock physical properties and their uncertainties, and permits reliable simulations of fluid flow and heat recovery. At any step continuative investigations can be optimized by applying "Optimizing field exploration strategies".

Moreover, the application of the guideline strategies for exploration and exploitation of reservoirs as developed in this project are not limited to geothermal fields but can also be applied to hydrocarbons, CO_2-sequestation, or nuclear waste.

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