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Integrated Exploration Strategy 'ConvEx' to detect Hydrothermal Convection in the Subsurface

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ABSTRACT

Hydrothermal convection zones in the subsurface can strongly affect the subsurface temperature at reservoir depth and are therefore a major target for geothermal exploitation of low-enthalpy hydrothermal systems. However, their detection is still a challenging task. The standard exploration methods as e.g. 2D/3D seismics alone are insufficient to localize ascending hydrothermal fluid flow in the subsurface (i.e. convection cells). Furthermore, the mapping of convection cells along major faults zones is complicated by laterally variable fault zone permeabilities depending on their recent activity and their orientation to the in-situ stress field.

The intensity of hydrothermal convection expresses itself as thermal anomalies and in case of highly saline brines also by a shift in electrical resistivity so that the integration of electromagnetic (EM) surveying methods may provide the missing link. The lower resolution and non-unique results of EM methods can be compensated by integration of detailed structural models based on 3D seismic exploration data, detailed analysis of petrophysical properties and stratigraphic-sedimentary basin-analysis.

We present an integrated model approach, which combines a) high-resolution 3D seismics with b) magnetotelluric (MT),controlled source electromagnetic (CSEM) and gravity exploration data, parameterized with c) rock properties determined based on lab investigations on cores from reservoir depth as well as from borehole geophysical logs and d) fluid properties, validated by e) high-accuracy geothermal gradients determined in medium deep gradient wells and f) (in our case study) by two deep wells drilled for oil and geothermal exploration. The resulting thermo-hydro-mechanical models will simulate convection cells and through validation will enable to map where hot brines are ascending and thus define targets for future exploitation.

We present our approach for a local case study in the northern Upper Rhine Graben, Germany, where a detailed 3D model based on 3D seismic data as well as various deep exploration wells indicating positive and negative geothermal anomalies and thus hydrothermal convection along major fault zones are present. This data will be complemented by new exploration data (EM and gradient wells) to test and validate our exploration strategy and modelling approach, which eventually shall result in a best-practice exploration workflow for similar geothermal play types.

1. INTRODUCTION

Often, reservoir exploration is carried out using only few methods or the information stemming from limited number of exploration techniques are treated separately or is spread out over diverse compilations (Dezayes et al., 2017), which do not provide a comprehensive picture from the integration of different methods (Bär et al., 2018, 2020). An integration and inversion of these datasets of various methods and scales is not yet developed in geothermal exploration and often only applied for high-enthalpy geothermal reservoirs. In low- to medium-enthalpy deep geothermal resources in sedimentary basins, the strategy in exploration is an incremental process (Bruhn et al., 2010).

It starts with the analysis and evaluation of pre-existing data of the target region. More costly surface exploration techniques will acquire new data step by step to sharpen the resolution and reliability of the subsurface geological/geothermal model (e.g. 2D seismic covering a large area => focused 3D seismic to enhance 3D resolution) and to define the target in more detail. This process is necessary to reduce the exploration costs and to minimize exploration risks. Precise target reservoir definition is necessary for well path planning of a doublet and to design development and exploitation strategies (Blöcher et al., 2015). This is achieved by real-time updating of the subsurface model, reflecting the current state of our knowledge on the reservoir, which serves as a basis for go/no-go decisions. Within this strategy, only straight forward methods proven to give reliable data are usually budgeted. Any additional promising approaches, which may prove to be the next milestone in exploration development, can usually only be tested within third-party funded research projects.

Several geological, geophysical, and geochemical methods are applied in geothermal exploration which complement one another. Benefits and limitations of geophysical methods in deep geothermal exploration are described in Dezayes et al. (2017). However, none of the methods alone is able to give sufficient evidence to justify the investment for drilling. Standard seismic methods usually resolve the geological structures and seismic attribute analysis give additional arguments for fluid conduits but cannot directly image the presence of geothermal water. The presence of geothermal fluids and hydraulic activity can therefore only be proven by drilling into the structure. Different to the hydrocarbon industry the first well in a geothermal project has to prove the resource due to the high drilling costs (Sass et al., 2016). A second shot is usually not possible.

Especially fault zones are found to be hydraulic conduits for hydrothermal convection flows, which generate significant electrical resistivity contrasts that may be mapped using geophysical EM methods. However, in areas with a high level of industrialization and urbanization like the Upper Rhine Graben EM data are generally affected by human-generated noise (from railroad tracks, power cables, industrial facilities) that can obfuscate the relevant signal. In such challenging context passive EM such as Magnetotelluric (MT) techniques are thought not to be applicable at all. To overcome the noise problem controlled source electromagnetics (CSEM, Grayver et al., 2013; Streich, 2009) where either the borehole directly or shallow (<10 m) sources in combination with MT have been recently tested as a complementary exploration technique to give reliable results for both oil and gas and deep geothermal reservoirs (Streich et al., 2011, 2016; Schaller et al., 2017; Darnet et al., 2017; Tietze et al., 2015). Additionally, gravity surveys can complement the EM methods to detect hydraulically active fault zones, as these often exhibit increased fracture porosity. High porosities are directly related to negative density anomalies, which can be identified by inversion of the gravitational field. The ambiguousness of the EM and gravity methods may be overcome by adding structural and stratigraphic information from the well and 2D seismics.

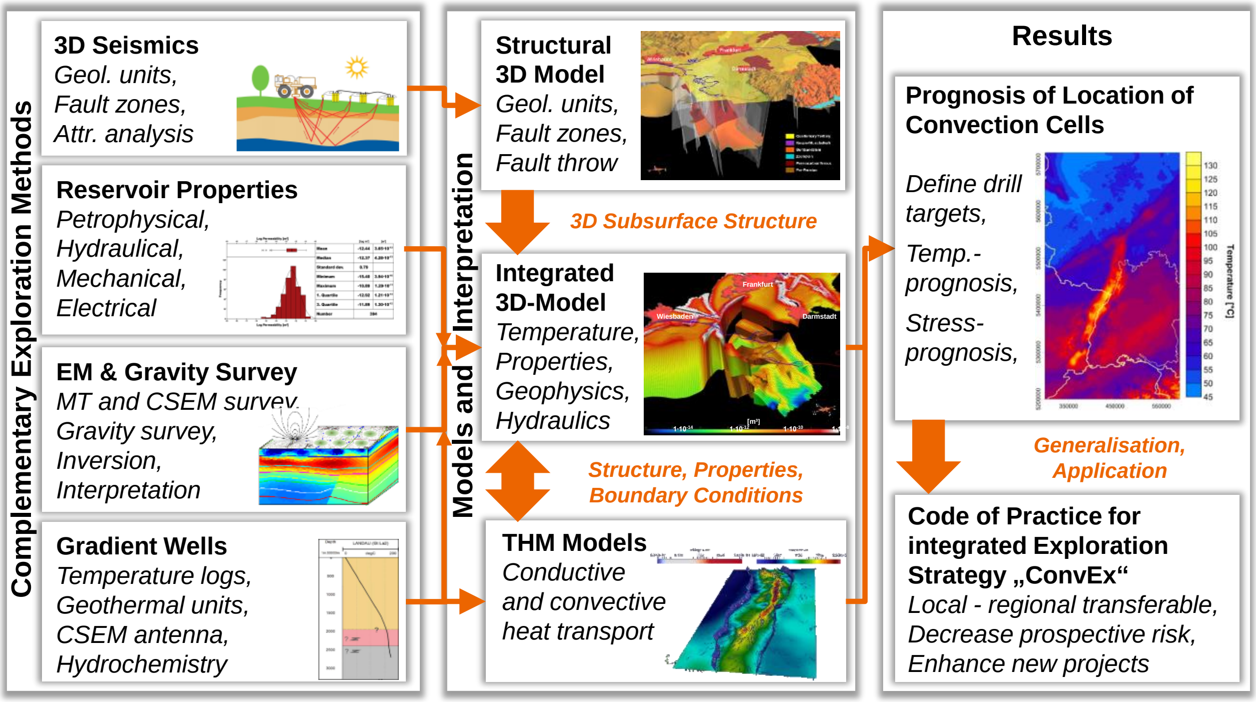

Figure 1: Workflow of the ConvEx integrated exploration strategy

In the area of our case study, the Upper Rhine Graben, a well-established geothermal exploration approach to map hydrothermal convection along fault zones is still lacking prior to drilling. To date high resolution structural mapping using 3D seismics together with information from offset wells are thought to be sufficient in enhancing the probability of success. After drilling Trebur GT1 into highly altered volcanic rocks apparently sealing the existing fracture network, this approach seems not to be sufficient any more at least in the northern Upper Rhine Graben. Geophysical datasets based on surface seismics alone are insufficient to map alterations as well as convection cells and thus both fossil and active hydrothermal systems. Mapping alteration is furthermore complicated by laterally varying intensity of alteration regardless of their diagenetic or hydrothermal origin. The intensity of alteration may however manifest itself also by a shift in electrical resistivity of the medium. Electromagnetic methods aiming at mapping earth resistivity in 3D may therefore provide the missing link for both alteration and convection cell mapping. They however lead to lower resolution images than seismics and non-unique results due to the diffuse nature of the EM fields in the earth. This limitation can be overcome by adding structural and stratigraphic information. In our particular case, the combination of high-resolution 3D datasets (e.g. 3D seismic) with lower-resolution EM (e.g. CSEM) and temperature gradient data (from gradient wells) should provide a robust approach for mapping high saline thermal fluids along fault zones, i.e. hydrothermal convection (Figure 1).

Nonetheless, these methods alone usually do not account for the exploration of all properties, which are required for predictive stochastic modelling (Vogt et al., 2010; Pyrcz and Deutsch, 2014) of the thermo-hydro-mechanical behavior of the reservoir (Guillou-Frottier et al., 2013; Jacquey et al., 2017). Thus, we aim to complete the exploration dataset by petrophysical core investigations and geophysical borehole log-based characterization of the reservoir formations, which allows for the development of empirical correlations between reservoir properties at different scales (Neuman et al., 2013). This together with an analysis of the hydrochemistry and fluid properties is unequivocally necessary to fill the gaps in exploration data and provide a ground-breaking enhancement in understanding and modelling of reservoir behavior (Cacace and Jaquey, 2017).

2. GEOTHERMAL SITUATION IN THE UPPER RHINE GRABEN AND CASE STUDY TREBUR (GERMANY)

After more than 30 years of research in the Upper Rhine Graben, drilling results demonstrated that sufficient amounts of natural fluids are trapped in the fractures of the deep-seated granitoids or in permeable Paleozoic to Mesozoic sedimentary units on top of it (Genter et al., 2018). This geothermal water is very saline (> 100 g/l) and circulates within the multiscale fault and fracture system of the Upper Rhine Graben. Temperature measurements and various modelling studies of regional fluid flow and heat transport ongoing since decades (Clauser, 1989, Clauser and Villinger, 1990, Pribnow and Clauser, 2000, Bächler et al., 2003, Baillieux et al., 2014, Vidal and Genter, 2018, Freymark et al., 2017, 2019) also proved that geothermal waters are associated to large scale convection loops with their deep roots localized in the granitic basement and their shallowest parts in the middle Triassic sedimentary formations (Genter et al., 2018). Thus, the main challenge for exploration of such geothermal targets is to be able to predict with the best accuracy, the temperature field at the top of the reservoir. Moreover, as the geothermal resource is trapped within a subvertical fracture system, the challenge is to be able to image the complex geometry of this fracture network close to the interface between the sedimentary cover and the basement (Genter et al., 2018). In the northern Upper Rhine Graben, deep geothermal exploration was unsuccessful so far, despite favorable predictions beforehand (Bär et al., 2011, Aretz et al., 2016). This demonstrates that predictions of the deep geothermal potential are associated with large uncertainties. Overcoming such uncertainties requires an understanding of the relevant physical processes driving deep fluid flow and heat transport, as well as the geothermal and pressure-(overburden-) history, the development of the stress field and the reconstruction of geochemical rock-fluid interactions in the history. To assess how structural and geological heterogeneities influence deep heat transport and what dynamic needs to be considered if predictions of temperature distributions and flow regimes have to be made, an as detailed as possible 3D representation of the subsurface structure and its geothermal properties is required.

A large and comprehensive dataset has been collected during exploration for the deep geothermal project Trebur, which will be used for our case study. Data comprise several 2D seismic lines, one large 3D seismic survey, gravity survey, magnetic survey, stratigraphic and geophysical logs from offset wells, as well as hydrochemical/isotopic data. This dataset is supplemented by literature data and outcrop analogue studies in the broader vicinity (Aretz et al., 2016, Molenaar et al., 2015). A detailed subsurface geological model has been set up as a basis for subsequent geomechanical and thermo-hydraulic modelling to find the most promising targets for hydrothermal exploitation. The target chosen to be the first deep geothermal project in the northern Upper Rhine Graben is located east of the community of Trebur near Groß-Gerau (Figure 2).

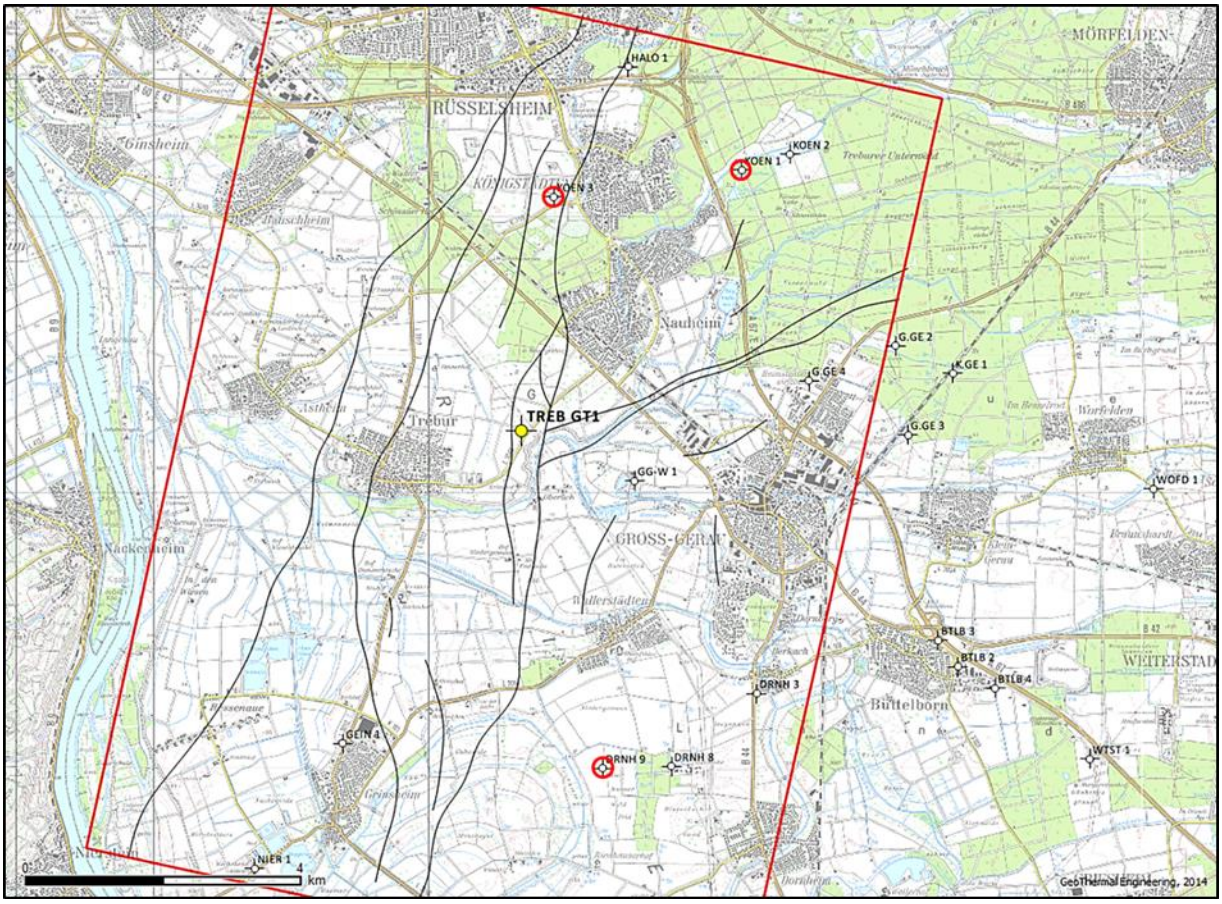

Figure 2: Study area for mapping hydrothermal convection and testing the "ConvEx" exploration workflow. Red box indicates the outline of the 3D seismic survey. Black lines: fault traces at 3.5 km depth interpreted from the 3D seismic. Red circles: offset wells with available stratigraphic and geophysical data. Yellow dot: Geothermal well Trebur GT1.

The envisaged fractured reservoir at approx. 3.5 km depth is defined by a sequence of volcanic rocks (basaltic lavas/sills and rhyolitic tuffs) intercalated in siliciclastic sediments of Permian age (Donnersberg formation, Rotliegend) crosscut by a fault zone proven to be active during Cenozoic times. The average geothermal gradient derived from offset wells is in the order of 5 K per 100 m. At reservoir depth formation temperature of up to 170 °C has been expected. Flow rates of 60 to 80 l/s have been expected to be realistic in highly fractured reservoirs associated with fault zones.

When drilling the first well Trebur GT1 in 2016 stratigraphy and structures have been encountered as predicted. From image logs open fractures are proven to be oriented in the same direction as predicted by the geomechanical model. However, in contrast to our expectations the open fractures within the envisaged reservoir were hydraulically inactive. Additionally, formation temperature was significantly less than expected (i.e. approx. 140 °C at 3.4 km depth). Both, relatively low temperature and absent hydraulics correlate with the occurrence of massive alteration encountered in the volcanic tuffs of the Donnersberg formation. This alteration is not known from offset wells in this extent and the nature of occurrence as well as the controlling factors of this alteration is under investigation. We assume that these alterations hindered, sealed or limited the growth of discrete fracture networks, the associated percolation and convective heat transport (i.e. hydrothermal convection). On the other hand, the massive alteration might be the outcome of past hydrothermal alteration and present a fossil hydrothermal system.

About 3.5 km further to the north, the well Königstädten 3 has been drilled into the same structure as the Trebur GT1 in 1957. The well drilled into top Rotliegend with total depth of 2492 m and a BHT of 152 °C (corrected). Assuming temperature as a proxy indicating hydrothermal convection, the conclusion is that there are major differences in hydraulics along strike of the fault with ascending hydrothermal fluid flow in the northern part. Unfortunately, the well Königstädten 3 has not reached the Donnersberg formation and was not drilled through the fault zone as the well Trebur GT1 was.

Within the study area Trebur (Figure 2) for combining exploration methods to map hydrothermal convection a fully interpreted high resolution 3D seismic already exists. Geophysical and lithological/stratigraphic data from two deep wells reaching the same fault zone but with significantly different geothermal gradients are present. Additional shallow gradient wells (approx. 500 m deep) are planned to add thermal data. Within the same gradient wells water samples will be analyzed for hydrochemistry and isotopic signatures indicating ascent of deep fluids along fault zones. These will give an independent hint on the presence of hydrothermal convection. Total dissolved solids of the NaCl dominated thermal fluid in the northern Upper Rhine Graben reach 120 g/l i.e. a very high conductivity giving a high resistivity contrast between the “dry” formation and areas of hydrothermal convection in fractured rock masses within fault zones. As the electrical resistivity of rocks varies over many orders of magnitude, massive alterations within volcanic tuffs interbedded in basaltic lava layers as encountered in the well Trebur GT1 will have an influence on the resistivity contrast depending on the pore and crystal water content of the alteration products (clay minerals). Clay minerals from alteration as well as fracturing usually decrease resistivity of the rock mass. The electrical resistivity of the encountered alteration clay minerals will be measured in the laboratory and evaluated in terms of their influence on the resistivity contrast in the subsurface.

3. EXPLORATION CONCEPT CONVEX

3.1 Lab- and Log-based Petrophysical Rock and Reservoir Characterization

As material for the investigation of the petrophysical rock properties of the relevant geological units of the investigation area, drill cuttings, cores from exploration analog areas and drill cores from old deep boreholes of the hydrocarbon industry will be used. Most of these are archived and accessible in the core storage facilities of EMPG GmbH and Wintershall AG. The following rock properties shall be investigated as input data for the thermo-hydraulic modelling and the inversion of the EM measurements: Pure and bulk density, porosity, permeability, thermal conductivity, thermal diffusivity, heat capacity, compression and shear wave velocity (dynamic modulus of elasticity and Poisson's ratio) and most important electrical conductivity and resistivity. These properties will be determined on both oven-dry and saturated samples to allow conversion to in-situ conditions. It is planned to use different fluids for sample saturation (e.g. distilled water, artificial brines with TDS contents corresponding to the thermal brines of the Upper Rhine Graben). In addition, selected samples will be investigated under pressure and temperature conditions close to those of the reservoir in order to take into account possible dependencies of the properties on the in-situ conditions during modelling.

For the interpretation (inversion) of the CSEM and MT data, in-situ measured petrophysical parameters are used in addition to the parameters obtained by laboratory measurements. These are derived from existing borehole geophysical log data from offset boreholes of the hydrocarbon industry (e.g. Königstädten 3, Weiterstadt 1, Gimbsheim 2) and the Trebur GT1 borehole. This includes in particular the electrical conductivity (or its inverse resistivity). These data also serve to attribute the integrated underground model.

Individual representative wells with particularly good data (complete logs from surface to Rotliegend) and as many core sections as possible will be selected. This covers the entire stratigraphic sequence in the investigated area and allows to analyze the required properties for the parameterization of the models on different scales. All results of the laboratory investigations and the log evaluation will be summarized using the established database structure for the collection of rock-physical data from multiscalar data sets (Bär et al., 2017, Linsel et al., 2018, 2020). This data structure enables the evaluation according to petrological, sedimentary, stratigraphic or lithofacies aspects (Sass and Götz, 2012) and the automated derivation of statistical characteristic values or empirical correlations for the units of the 3D underground model. With the help of geostatistical methods and proven empirical correlations between characteristic values of rock samples (Mielke et al., 2017) and characteristic values determined from borehole logs (Fuchs and Förster, 2013, Fuchs et al., 2013, 2015), the reservoir characteristic values can be calculated and scaled up for modelling (Gu et al., 2017, Rühaak et al., 2015). For stochastic modelling, the statistical distribution of the characteristic values of the individual relevant properties represents the limits for iterative parameterization.

3.2 EM and Gravity Exploration Campaign

The planned electromagnetic exploration will be conducted in the area covered by the 3D seismics (see red rectangle in Figure 2). Due to the proximity to various villages and industrial facilities (e.g. also Frankfurt Airport), very high electromagnetic interference levels are to be expected in this area, which strongly impair in particular MT measurements. MT measurements are based on naturally occurring electromagnetic field variations, which generally have much lower amplitudes than the interference signals. Using the

Remote Reference method, the data may at least be partly used to estimate background conductivities, which in turn are required for the planning of CSEM measurements. Therefore, in a first step, MT measurements are to be carried out distributed over the entire measurement area. The MT measurements pursue the following objectives:

- An overview of the noise level in the measuring area is to be obtained. Areas with particularly high interference levels should generally be avoided for the installation of receiver stations.
- The MT data are processed using the permanent Remote Reference Station of the GFZ and the latest statistical methods developed by the GFZ (Ritter et al., 1999; Weckmann et al., 2005; Platz and Weckmann, 2019). A rough model of the background conductivities is generated from the MT data.
- Based on this model of background conductivities, existing borehole logs, and structural information (3D seismics), 3D CSEM simulation calculations are performed to determine an optimal survey layout for the CSEM measurements.

For the CSEM main measurement, the entire measurement area is to be surveyed area-wide with a large number of simultaneously registering receiver stations and from several transmitter positions. In contrast to classical MT measurements, which are based on temporary, roll-along installations of the measuring stations, it is important for CSEM measurements to work with as large a number of simultaneously registering receivers as possible in order to record the spatial course of the generated EM fields in their entirety. The electromagnetic source fields are then generated by varying transmission positions. The active sources of the CSEM consist of three electrical dipoles with approximately one kilometer long cables.

In the night hours, with CSEM transmitters switched off, the natural signals of the MT can be recorded (in addition to the still existing interference signals). This results in the possibility of a joint inversion of MT and CSEM data. With MT data, a greater probing depth is normally achieved, while the CSEM data have a much better signal/noise behavior. Compared to the MT, CSEM data also have a better resolution for poorly conducting structures in the subsurface.

Based on the processed data (transfer functions), the distribution of the electrical conductivity must be derived laterally and with depth. In particular, the calculation of three-dimensional (3D) inversions requires a lot of memory and computing power on large, parallel-processing computer clusters (HPC). Since CSEM has to consider the spatial distribution of the fields (transmission geometry) in principle, the equation systems to be solved are always a 3D problem regardless of the complexity of the subsurface. In recent years, the GFZ and others have significantly advanced the development and application of 3D inversion tools, including 3D MT (ModEM; Egbert and Kelbert, 2012; Kelbert et al., 2014), 3D CSEM (Inv3D, Grayver et al., 2013) inversion codes, and joint 3D inversion of MT and CSEM (Meqbel and Ritter, 2015).

The data processing and inversion has the following objectives:

- Calculation of a 3D inversion model of the electrical conductivity with the depth from CSEM data. Comparison of inversion scenarios and inversion parameterizations, derivation of a robust final model.
- Calculation of a 3D inversion model of the electrical conductivity with the depth from MT data (depending on data quality).
- Depending on the data availability calculation of a joint 3D CSEM-MT inversion.

In addition to the electromagnetic methods, the exploration of fault zones through gravity measurements is useful to obtain insights about the density distribution in the subsurface. In the area of interest, a gravity dataset was already acquired by the Leibniz Institute for Applied Geophysics (LIAG) and the Hessian Administration for Soil Management and Geoinformation (HVBG) which comprises about 50 point measurements. The distance between these stations varies considerably ranging from a few hundred to about 2.5 km. Within the ConvEx project, this dataset will be refined by additional measurements. Close to the identified faults, the resolution should be at least 250 m and it should not exceed 1 km in the remaining model area.

The existing as well as newly measured gravity data will then be processed with respect to instrument drift, tidal influences, gravimeter inclination, temperature variations, reference gravity field and the effects of measurement height, topography and masses between the station and reference level (e.g. Hinze et al. 2005). Interpolation of the processed point data will result in a high-resolution map of the Bouguer anomalies, which allows conclusions about the structure and composition of the subsurface. However, the observed gravity field represents a superposition of different geological sources. Especially the LAB, Moho, top of the lower crust and top of the crystalline basement generate a long-wavelength regional field which has to be separated from the residual field of the sedimentary units. We will follow two approaches to do this, each with their own strengths and weaknesses:

1. Frequency Filtering:
   The wavelength of gravity signals increases with the depth of the source. Accordingly, an analysis of the frequency content of the Bouguer anomalies by Fourier transformation is planned, which will enable a specific design of the frequency filters. By applying low-pass filters, long wavelengths are amplified resulting in a regional trend. High-pass filters amplify the short wavelengths of near-surface structures. Furthermore, band-pass filters can be used to obtain information about certain depth intervals (= gravity pseudo-tomography; e.g. Baillieux et al. 2014). But it should be noted that also near-surface horizons may generate long-wavelength signals when they are laterally extensive and relatively homogeneous, therefore distorting the filtering results.
2. Forward Modelling:
   As an alternative to filtering, the regional gravity field can also be determined by forward modelling. For this purpose, structural information about the lithospheric mantle and the crystalline crust will be compiled from e.g. seismic profiles, receiver functions or potential field studies. However, reliable data a generally sparse which might lead to uncertainties of several kilometers.

The reduced Bouguer anomalies are then the input for a 3D inversion. It is important to develop a realistic starting model of the density distribution that is derived mainly from the seismic data, borehole logs and petrophysical laboratory measurements. A stochastic inversion algorithm, like the Monte-Carlo-Markov-Chain method, will be used, which allows a statistical evaluation of the results e.g. regarding the model uncertainties (Mosegaard and Tarantola, 1995; Li and Oldenburg, 1998). Main outcome of the gravity inversion is a detailed 3D density model. Decreased density values close to fault zones indicate increased fracture porosity and thus hydraulic activity of the fault. Finally, the combination of results from the CSEM/MT and gravity surveys will contribute to significantly reduce the uncertainties and ambiguity of each method so that permeable zone can be reliably identified.

3.3 Gradient Wells and Analysis of the Thermal Field

It is planned to drill three to five middle-deep (up to 500 m deep) wells for numerous additional measurements to complement the exploration dataset. The planned borehole geophysical measurement program will measure temperature, salinity, conductivity, natural gamma radiation and resistivity. These investigations will be supplemented by further logs, e.g. for determining the exact course of the borehole, which are recommended by mining law.

Continuous temperature profiles should be repeated in each well at least three different times (e.g. spring, summer, autumn) in order to identify near-surface seasonal variations and to ensure that the well is in equilibrium with the undisturbed underground temperature ("thermal equilibrium"), i.e. at least one undisturbed temperature-depth profile per well. These are needed to validate the thermohydraulic models. In addition to the profiles of the gradient boreholes, a continuous temperature-depth profile is to be measured in the deep borehole Trebur GT1 which is to be used both for the analysis of the layer-related geothermal gradients and for the validation of the thermohydraulic models.

The correlation of the lithological drilling profiles with the thermophysical and hydraulic rock parameters from is used for the interpretation of the continuous temperature-depth profiles. Thus, areas of convective heat transport (e.g. in the near-surface aquifers of the Quaternary) can be distinguished from areas of conductive heat transport. In the rather impermeable strata of the Tertiary (from depths of approx. 20 to 100 m below ground level), apart from large fault systems up to the upper edge of the Rotliegend reservoir, dominant conductive heat transport conditions can be expected, which have already been demonstrated at numerous sites in the Upper Rhine Graben (Maurer et al., 2018).

Water samples will also be taken in the gradient boreholes and examined for their water chemistry and isotopy. The signatures allow the origin and residence time of the water in the subsoil to be reconstructed. This information complements the data basis on the rise of deep waters and thus serves to interpret the temperature field in the subsurface.

4. INTEGRATED MODELLING

The integrated modelling serves the iteration of the selected attribution on the one hand with the inversion of the results of the CSEM measurements as well as the thermo-hydraulic-mechanical modelling. In a first step, a starting model is to be created from the data already available before the start of the project. This model will then be used for first thermohydraulic simulations and the comparison with temperature measurements. During the further course of the project, the models will then be adapted to the various exploration methods with the newly acquired data and finally used for modified thermohydraulic simulations.

On the basis of the interpretation of the 3D seismic exploration of the permit field Trebur-Groß-Gerau and for the regional scale the 3D geological-geothermal model from the project "Hessen 3D 2.0" a 3D geological structural model shall be created. The inclusion of the regional scale is particularly important in order to be able to define the effective large-scale boundary conditions for thermal-hydraulic modelling on the local scale.

In order to attribute the model units with rock-physical or reservoir geological parameters, all data from the different parts of exploration works will be integrated with each other using the existing database application (Bär et al., 2017, Linsel et al., 2018). The previously defined geological model units are attributed with the subsoil properties derived from the petrophysical investigations, the evaluation of the borehole geophysics and the results from gradient wells. In particular, the scale, pressure and temperature dependence must be taken into account and common methods for upscaling (e.g. Rühaak et al., 2015) must be applied.

In the course of this, the results of the seismic attribute analyses already carried out in the AuGE project (Reinecker et al., 2015) are to be used for the detection of areas in which special geological conditions (fault zones, damage zones, degree of alteration, etc.) can be expected. With the help of these, these geothermally particularly interesting areas can be attributed separately in the integrated underground model.

With the described inversion calculations, three-dimensional electrical conductivity and density models of the subsurface are obtained, which best adapt (explain) the obtained CSEM/MT and gravity data. In addition to the conductivity models derived from the CSEM/MT measurements, it is often helpful to include further information in the modelling/inversion. For example, the lower edges of well conducting layers in CSEM/MT models are poorly resolved due to methodological reasons. With the aid of structure imaging 3D seismics, it should be possible to specify layer thicknesses or layer progressions as additional information in the initial models for inversion and to record them during the inversion process. Chemical investigations of rock waters and petrophysical measurements on rock samples can further limit the possible electrical conductivities to be expected for inversion. Borehole logs of the electrical conductivity can provide important additional information on the resistances in the immediate vicinity (cm area) of boreholes.

The integrated modelling has the following objectives:

- With constrained inversions the obtained conductivity models shall be investigated for consistency with geological / hydrological framework conditions.
- Model units are to be derived which explain both the CSEM/MT and gravity data as well as the additional exploration data.
- areas in the measurement area that appear to be particularly promising with regard to further deep drilling / geothermal exploration shall be identified.

5. UNCERTAINTY MODELLING

With the integrated model completed, it is within the scope of the ConvEx approach to create an uncertainty model to assess the results of the integrated model. While this is common in the hydrocarbon industry to reduce the risk of failure for exploration projects, this is still not commonly applied within the geothermal industry. As proposed by, e.g. Witter et al. (2019), uncertainty modelling will reduce the potential failure of subsequent wells, be it in exploration or production stage. Using a stochastical approach quantifies the uncertainty and with it will give an answer on the reliability of the integrated model (Caers, 2012; Witter et al. 2019).

In our stochastical uncertainty analysis model we will use any parameter that has a defined uncertainty parameter. Since the different complementary exploration methods as shown in figure 1 have different ranges of uncertainties, a collection of variables which ranges shall be defined as input for the uncertainty model. Typical uncertainties in a geological setting are caused, amongst others, in seismic by resolution, velocity models, and wavelength (Caers, 2012). Borehole driven uncertainties can influence both topology (e.g, by depth measurement and deviation) or intrinsic rock properties due to, for instance, measurement errors (Moore et al., 2011). Besides the other uncertainties, the modelling itself will have uncertainties due to interpretation and interpolation of the available data.

In practice, this means all input parameters of the aforementioned seismic interpretation of the Trebur-Groß-Gerau surveys and the Hessen 3D 2.0 model will have to be analyzed for their uncertainty components, as well as the uncertainties of the petrophysical measurements. Spatial distribution relationships between measurements, for instance porosity, shall be taken into account to define and set limits for the uncertainty model (Wellmann and Caumon, 2019).

Using all of the uncertainty parameters for the stochastic model many models will be created within these the parameters. As each uncertainty parameter has a distribution of occurrence (e.g, gaussian or triangle), these will create equal valid outcomes. With many realizations available, we can derive where and how the uncertainty is for each property. A standard deviation model can be created to express the uncertainty visually. With it, we can derive whether mitigation actions should be taken to reduce the risk of failure.

If so decided, to reduce the risk of failure, a sensitivity analysis will indicate which variables have the most important contribution to the uncertainties. The most common method for geological purposes is the response surface method in combination with an appropriate experimental design (Fenwick et al., 2014; White et al. 2001). In the current case around Trebur, both first and second order analysis should be considered, depending on the response investigated (e.g. structural uncertainty).

The uncertainty and sensitivity models have the following objectives:

- Through the use of stochastic uncertainty modelling the geological uncertainty and variability within the target region should be quantified;
- Establish which data is most influential for geological uncertainty thus assisting in, if needed, what type of additional investigation is most prudent to limit the risk and which acquisition technique might be most helpful.

6. THM-MODELLING

Within the scope of the planned thermal-hydraulic(-mechanical-chemical) models, all data and observations available for the study area are to be integrated into numerical models in order to carry out three-dimensional coupled simulations of the thermal-hydraulic and thermal-hydraulic-mechanical (THM-) processes in the underground. Accordingly, the numerical simulations require:

(i) a sufficiently accurate representation of the geological units and disturbances in the subsurface, i.e. a 3D model,
(ii) knowledge of the hydraulic, thermal and mechanical rock and reservoir properties, and
(iii) knowledge of the pore fluid properties.

Information for the investigated area is already available at the beginning of the project. In addition, the simulations are designed in such a way that all additional measurement data and models collected during the project can be integrated in due time (updatable models).

The open-source software "MeshIt" was developed by Cacace and Blöcher (2015) for the numerical mapping of the three-dimensional geometries of hydrogeological units (including fault zones). The resulting numerical grids form the basis for the execution of coupled THM simulations, for which the open-source software "Golem" developed by Cacace and Jacquey (2017) is available. Recently, the basic methodology - numerically simulating coupled heat transport processes on the basis of geothermal 3D models - has already been successfully used to determine variations of the geothermal potential in the underground (e.g. for Berlin; Sippel et al., 2013; Kastner et al., 2013). How variations in the structure and orientation of fault zones under given stress conditions affect the hydraulic conductivity of a geothermal reservoir could be shown with the help of coupled TH modelling using the example of a carbonate reservoir in southern Germany (Cacace et al., 2013). Studies at the in-situ geothermal laboratory Groß Schönebeck (Blöcher et al., 2015) have shown that the numerical methods are also suitable for developing best-case scenarios for the configuration of production and injection wells. Finally, it was also possible to quantify the influence of the extraction and re-injection of fluids on the transport properties of the rocks, i.e. how the associated thermo- and poroelastic effects affect the mechanical behavior of the reservoir and thus its sustainability (Jacquey et al., 2017).

The modelling is planned to be divided into two phases. The aim of the first phase is to quantify the THM processes for the subsoil of the entire study area under in situ stress conditions. Taking into account the hydrogeological conditions, the numerical simulations allow in particular to test different working hypotheses on the causes of the field observations at the borehole "Trebur GT1". The aim is therefore to characterize the natural factors controlling the coupled processes and thus to explain the temperatures and flow rates of the fluids observed at the borehole in the pore space and fracture network of the rocks.

In the thermal-hydraulical modelling in particular, the range of variation of the geothermal characteristic values by geostatistical methods will be taken into account and, in addition, the pressure, temperature and thus depth dependence of the properties of geological units and fault zones will be implemented. For the validation all available and in the gradient drillings newly obtained underground temperature measurements will be used and the models will be adapted iteratively until an optimal fit between simulation result and all actual measurements is achieved. This should allow for an as accurate localization of convection cells as possible.

The second phase will focus on numerical simulations of different scenarios for the production of geothermal energy from the study area on the basis of the optimized models. Once again, coupled THM processes in the subsurface will be quantified - in this case, however, those that accompany the production and injection of thermal brine in the sphere of influence of a geothermal borehole. By testing different production/injection scenarios, the best possible configuration for a geothermal well in the investigated area can be determined, i.e. an optimal location with respect to the hydrogeological structure (including major disturbances) and also relative to the already existing well "Trebur GT1". In addition, various scenarios of hydraulic stimulation by duplicate operation or targeted measures are simulated and analyzed, taking into account the in-situ stress conditions characterized in the first phase. The evaluation of all tested scenarios is initially carried out with regard to their production potential and operational sustainability (over 30 and/or 100 years of operation). Finally, the numerical models also serve to assess the safety during geothermal use, because certain changes in temperature and pore pressure conditions can potentially lead to a mechanical reactivation of fault zones.

The THM modelling visualizes the implications of the different measurement data interpretations (borehole data, seismics, CSEM, gravity, etc.) for underground processes directly, so that the THM modelling for the ConvEx project represents a link between the measurement campaigns and the targeted planning of operational activities.

7. CONCLUSION

We presented an integrated model approach, which combines

a. high-resolution 3D seismics with
b. lower-resolution EM (MT, CSEM) and gravity exploration data parameterized with
c. rock properties determined based on lab investigations on cores from reservoir depth as well as from borehole geophysical logs and
d. fluid properties, validated by
e. high-accuracy geothermal gradients determined in medium deep gradient wells and
f. (in our case study) by two deep wells drilled for oil and geothermal exploration.

The resulting thermal-hydro-mechanical models will simulate convection cells and through validation will enable to map where hot brines are ascending and thus define targets for future exploitation.

The final aim is to develop up guidelines and an interactive work-flow for an extended exploration strategy for low enthalpy deep geothermal reservoirs, such as are predominant in Central Europe. In this project the learning curve, which will be passed through in the framework of the project, shall be used to give a recommendation for a compact, comparatively cost-effective exploration strategy, which promises a minimization of the exploration risk. In particular, aspects of transferability to comparable (central and southern Upper Rhine Graben) but also other geological-tectonic conditions (Molasse Basin, North German Basin, etc.) will be considered with this tool.

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REFERENCES

Aretz, A.; Bär, K.; Götz, A. and Sass, I. Outcrop analogue study of Permocarboniferous geothermal sandstone reservoir formations (northern Upper Rhine Graben, Germany): Impact of mineral content, depositional environment and diagenesis on petrophysical properties. *Int. J. Earth Sci.* **105**, (2016), 1431–1452.

Aretz, A.: Aufschlussanalogstudie zur geothermischen Reservoircharakterisierung des Permokarbons im nördlichen Oberrheingraben. *Dissertation*, TU Darmstadt. (2015)

Arndt, D.: Geologische Strukturmodellierung von Hessen zur Bestimmung von Geo-Potenzialen. *Dissertation*, TU Darmstadt. 199 p. (2012)

Bächler, D.; Kohl, T.; Rybach, L. Impact of graben-parallel faults on hydrothermal convection—-Rhine Graben case study. *Phys. Chem. Earth* **28**, (2003), 431–441.

Baillieux, P.; Schill, E.; Abdelfettah, Y.; Dezayes, C. Possible natural fluid pathways from gravity pseudo-tomography in the geothermal fields of Northern Alsace (Upper Rhine Graben). *Geotherm. Energy* **2**, (2014), 16p.

Bär, K., Arndt, D., Fritsche, J.-G., Götz, A.E., Hoppe, A., Kracht, M. and Sass, I.: 3D-Modellierung der tiefengeothermischen Potenziale von Hessen – Eingangsdaten und Potenzialausweisung. *Z. dt. Ges. Geowiss*., **162 (4)**, (2011), 371-388, 7 Abb., 4 Tab., Stuttgart (Schweizerbart).

Bär, K.: Untersuchung der tiefengeothermischen Potenziale von Hessen. *Dissertation*, Technische Universität Darmstadt, 280 p. (2012)

Bär, K., Reinsch, T., Sippel, S., Strom, A., Mielke, P. and Sass, I.: P³ - International PetroPhysical Property Database. - *Proceedings*, 42nd Workshop on Geothermal Reservoir Engineering, Stanford University, Stan-ford, California, February 13-15, 2017, (2017)

Bär, K., Sippel, J., Hintze, M., Koltzer, N., Weinert, S., Fritsche, J.-G., Kracht, M., Scheck-Wenderoth, M., Sass, I.: Determining deep geothermal potentials based on integrated multi-scale datasets and models: case study of the Federal State of Hesse (Germany). *Proceedings*, Geophysical Research Abstracts Vol. 20, EGU2018-14263, EGU General Assembly 2018, (2018).

Bär, K., Bott, J., Hintze, M., Weinert, S., Koltzer, N., Schääfer, R., Scheck-Wenderoth, M., Sass, I.: Assessment of Deep Geothermal Resources and Potentials with a Multi-Criteria Approach Based on Multi-Scale Datasets and Models. *Proceedings*, World Geothermal Congress 2020 Reykjavik, Iceland, April 26 – May 2, (2020).

Blöcher, G., Cacace, M., Reinsch, T. and Watanabe, N.: Evaluation of three exploitation concepts for a deep geothermal system in the North German Basin. *Computers & Geosciences,* **82**, (2015), 120-129.

Bruhn, D., Manzella, A., Vuataz, F., Faulds, J., Moeck, I. and Erbas, K.: Exploration methods. In: Huenges, E. (Ed.): Geothermal Energy Systems. Wiley-vch Verlag GmbH & Co KgaA, (2010), pp.37-112.

Bujakowski, W., Barbacki, A., Czerwinska, B., Pajak, L., Pussak, M., Stefaniuk, M. and Trzesniowski, Z.: Integrated seismic and magnetotelluric exploration of the Skierniewice, Poland, geothermal test site. *Geothermics*, **39**, (2010), 78–93.

Cacace M. and Blöcher, G.: MeshIt—a software for three dimensional volumetric meshing of complex faulted reservoirs. *Environmental Earth Sciences*, **74 (6)**, (2015), 5191–5209.

Cacace M. and Jacquey, A.: Flexible parallel implicit modelling of coupled Thermal-Hydraulic-Mechanical processes in fractured rocks. *Solid Earth*, **8**, (2017), 921–941.

Cacace M., Blöcher, G., Watanabe, N. Moeck, I., Börsing, N, Scheck-Wenderoth, M, Kolditz, O. and Huenges, E.: Modelling of fractured carbonate reservoirs: outline of a novel technique via a case study from the Molasse Basin, southern Bavaria, Germany. *Environmental Earth Sciences*, **70 (8)**, (2013), 3585–3602.

Caers, J., 2012. Modeling uncertainty in the earth sciences: Includes index. Wiley, Hoboken, NJ, 229 pp.

Clauser, C. Conductive and Convective Heat Flow Components in the Rheingraben and Implications for the Deep Permeability Distribution. In: Hydrogeological Regimes and Their Subsurface Thermal Effects; Beck, A.E., Garven, G., Stegena, L., Eds.; American Geophysical Union: Washington, DC, USA, **47**, (1989), pp. 59–65.

Clauser, C.; Villinger, H. Analysis of conductive and convective heat transfer in a sedimentary basin, demonstrated for the Rheingraben. *Geophys. J. Int.* **100**, (1990), 393–414.

Darnet et al. (2017a): 3D resistivity imaging with the CSEM method – examples from Czech Republic and France. In: the IMAGE consortium (eds.): IMAGE – Beyond a standardized workflow for geothermal exploration. *Deliverable* D2.05. 130 p.

Darnet et al. (2017b): Controlled-Source Electromagnetic Surveying for geothermal exploration in deep sedimentary and basement areas. *Proceedings*, IMAGE final conference – Novel approaches for Geothermal Exploration, 4-6 Oct. Akureyri, Iceland

Dezayes, C. and the IMAGE working group: Proposition for integrated exploration method in sedimentary basin context. Public deliverable IMAGE-D8.05 of the project IMAGE Integrated Methods for Advanced Geothermal Exploration Grant Agreement Number 608553. (2017)

Egbert, G. D., and Kelbert, A.: Computational recipes for electromagnetic inverse problems. *Geophysical Journal International*, **189**, (2012), 251-267.

Fuchs, S. and Förster, A.: Well-log based prediction of thermal conductivity of sedimentary successions: a case study from the North German Basin. *Geophys. J. Int.* (2013) doi: 10.1093/gji/ggt382

Fuchs, S., Schütz, F., Förster, H.-J. and Förster, A. (2013): Evaluation of common mixing models for calculating bulk thermal conductivity of sedimentary rocks: Correction charts and new conversion equations. *Geothermics*, **47**, (2013), 40– 52

Fuchs, S., Balling, N. and Förster, A. (2015): Calculation of thermal conductivity, thermal diffusivity and specific heat capacity of sedimentary rocks using petrophysical well logs. *Geophys. J. Int.,* **203**, (2015), 1977–2000 doi: 10.1093/gji/ggv403

Fenwick, D., Scheidt, C., Caers, J., 2014. Quantifying Asymmetric Parameter Interactions in Sensitivity Analysis: Application to Reservoir Modeling. *Math Geosci* **46 (4)**, 493–511.

Freymark, J., Sippel, J., Scheck-Wenderoth, M., Bär, K., Stiller, M., Kracht, M. and Fritsche, J.-G.: Heterogeneous crystalline crust controls the shallow thermal field – a case study of Hessen (Germany). *Energy Procedia*, **76**, (2015), 331-340. DOI: 10.1016/j.egypro.2015.07.837.

Freymark, J., Bott, J., Cacace, M., Ziegler, M., Scheck-Wenderoth, M. Influence of the Main Border Faults on the 3D Hydraulic Field of the Central Upper Rhine Graben. *Geofluids* **21**, (2019),

Freymark, J., Sippel, J., Scheck-Wenderoth, M., Bär, K., Stiller, M., Fritsche, J.-G. and Kracht, M. The deep thermal field of the Upper Rhine Graben. *Tectonophysics*, **694** (Suppl. C), (2017), 114–129.

Geiermann, J. and Schill, E.: 2-D magnetotellurics at the geothermal site at Soultz-sous-Forêts: resistivity distribution to about 3000 m depth. *Comptes Rendus Geosciences*, **342**, (2010), 587–599.

Genter A., Vidal J., Baujard C., Cuenot N., Dalmais E., Glaas C., Hehn R., Maurer V., Mouchot J. and Richard A.: Recent geothermal exploration and exploitation of hidden basement in the Upper Rhine Graben for producing heat or electricity, *Proceedings.* International Workshop on Hot Dry Rock Resource Exploration and Enhanced Geothermal System Engineering, 18-19th September 2018, Changchun, Jilin University, China (2018).

GeORG-Projektteam: Geopotenziale des tieferen Untergrundes im Oberrheingraben, Fachlich-Technischer Abschlussbericht des INTERREG-Projekts GeORG, Teil 1. – LGRB-Informationen, 28: 103 p.; Freiburg i.Br. (2013)

Guillou-Frottier, L., Carrė, C., Bourgine, B., Bouchot, V., Genter, A.: Structure of hydrothermal convec-tion in the Upper Rhine Graben as inferred from corrected temperature data and basin-scale numerical models. *Journal of Volcanology and Geothermal Research*, **256**, (2013), 29–49, doi: 10.1016/j.jvolgeores.2013.02.008

Grayver, A. V., Streich, R. and Ritter, O.: Three-dimensional parallel distributed inversion of CSEM data using a direct forward solver. *Geophysical Journal International*, **193(3)**, (2013), 1432-1446

Grayver A., Streich R. and Ritter O.: 3D inversion and resolution analysis of land-based CSEM data from the Ketzin storage formation. *Geophysics*, **79(2)**, (2014), E101-E114.

Gu, Y., Rühaak, W., Bär, K. and Sass, I.: Using seismic data to estimate the spatial distribution of rock thermal conductivity at reservoir scale. *Geothermics*, **66**, (2017), 61-72, doi:10.1016/j.geothermics.2016.11.007

Hinze, W. J.; Aiken, C.; Brozena, J.; Coakley, B.; Dater, D.; Flanagan, G. et al.: New standards for reducing gravity data: The North American gravity database. *Geophysics*, **70 (4)**, (2005), J25-J32. DOI: 10.1190/1.1988183.

Hoselmann, C. and Lehné, R.: Die quartärgeologische Entwicklung und ein geologisches 3D-Modell des nördlichen Oberrheingrabens. *Geol. Jb. Hessen*, **138**, (2014), 57-73.

Jacquey, A. B., Cacace, M., Blöcher, G., Watanabe, N., Huenges, E. and Scheck-Wenderoth, M.: Thermo-poroelastic numerical modelling for enhanced geothermal system performance: Case study of the Groß Schönebeck reservoir. *Tectonophysics*, **684**, (2017), 119–130.

Kastner, O., Sippel, J., Scheck-Wenderoth, M. and Huenges, E.: The deep geothermal potential of the Berlin area. *Environmental Earth Sciences*, **70 (8)**, (2013), 3567–3584.

Kelbert, A., Meqbel, N., Egbert, G. D., and Tandon, K.: ModEM: A modular system for inversion of electromagnetic geophysical data. *Computers & Geosciences*, 66, (2014), 4053.

Kraml, M., Jodocy, M., Reinecker, J., Leible, D., Freundt, F., Al Najem, S., Schmidt, G., Aeschbach, W. and Isenbeck-Schroeter, M.: TRACE: Detection of Permeable Deep-Reaching Fault Zone Sections in the Upper Rhine Graben, Germany, During Low-Budget Isotope-Geochemical Surface Exploration. *Proceedings*, European Geothermal Congress 2016, Strasbourg, France. (2016)

Li, Y., Oldenburg, D.W.: 3-D inversion of gravity data, *Geophysics*, **63**, (1998), 109-119.

Linsel, A., Greb, M. D., Bär, K., Hornung, J., Hinderer, M.: Bridging Information Gaps in Reservoir Studies – Archiving and Providing Information for Reservoir Studies (APIRS). *Proceedings*, AAPG Annual Convention and Exhibition: Salt Lake City. (2018)

Linsel, A., Greb, M. D., Bär, K., Hornung, J., Hinderer, M.: GeoReVi – A Tool for Integrated Knowledge Discovery in Databases (KDD) and Information Management for Comprehensive Reservoir Characterization. *Proceedings*, World Geothermal Congress 2020, Reykjavik, Iceland, April 26 – May 2, (2020).

Moore, W., Zee, M., Bratton, T., 2011. Uncertainty Analysis in Well-Log and Petrophysical Interpretations, in: Ma, Y.Z., La Pointe, P.R. (Eds.), Uncertainty Analysis and Reservoir Modeling. American Association of Petroleum Geologists, pp. 17–28.

Maurer, V., Auchholzer, C., Richard, A., Harlé, P., Hehn, R., Genter, A. and Duringer, P.: Geothermal reservoir temperature estimation derived from gradient wells in a continental rift context (Upper Rhine Graben). *Proceedings*, 43rd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 12-14, 2018, SGP-TR-213, (2018)

Meqbel, N. and Ritter, O.: Joint 3D inversion of multiple electromagnetic datasets. *Geophysical Prospecting*, **63**, (2015), 1450-1467. http://doi.org/10.1111/1365-2478.12334

Mielke, P., Bär, K. and Sass, I.: Determining the relationship of thermal conductivity and compressional wave velocity of common rock types as a basis for reservoir characterization. *J. Appl. Geophys.* **140**, (2017), 135-144, doi:10.1016/j.jappgeo.2017.04.002

Molenaar, N., Felder, M., Bär, K. and Götz, A.E.: What classic greywacke (litharenite) can reveal about feldspar diagenesis: An example from Permian Rotliegend sandstones in Hessen, Germany. *Sedimentary Geology* **326**, (2015), 79-93. DOI: 10.1016/j.sedgeo.2015.07.002.

Mosegaard, K., Tarantola, A.: Monte Carlo sampling of solutions to inverse problem. *J. Geophys. Res.*, **B7**, (1995), 12431-12447. DOI: 10.1029/94JB03097

Neuman, S.P., Di Federico, V.: Multifaceted nature of hydrogeologic scaling and its interpretation. *Rev Geophys*, **41**, (2003), 1014. doi: 10.1029/2003RG000130

Patzer, C., Tietze, K. and Ritter, O.: Steel-Cased Wells in 3-D Controlled Source EM Modelling, *Geophys. J. Int.*, **209**, (2017), 813–826.

Patzer, C., Tietze, K. and Ritter, O.: Time-lapse CSEM inversion using focusing regularization techniques for reservoir monitoring. *Extended abstract*, Society of Exploration Geophysicists International Exposition and 87th Annual Meeting, Houston, TX, USA., (2017) oral presentation.

Philipp, S.L., Bauer, J.F. and Meier, S.: Verbundprojekt AuGE: Aufschlussanalogstudien und ihre Anwendbarkeit in der geothermischen Exploration – Untersuchung von Störungszonen im Aufschluss und die Ermittlung optimaler Bohrzielpunkte - Schlussbericht Teilprojekt C – FKZ: 0325302C, 34 p. (2015)

Platz, A. and Weckmann, An automated new pre-selection tool for noisy Magnetotelluric data using the Mahalanobis distance and magnetic field constraints, *Geophysical Journal International*, **218(3)**, 2019, 1853–1872, https://doi.org/10.1093/gji/ggz197.

Pribnow, D.; Clauser, C. Heat and fluid flow at the Soultz hot dry rock system in the Rhine Graben. *Proceedings*, World Geothermal Congress (2000), Kyushu, Tohoku, Japan, 28 May–10 June 2000.

Pyrcz, M.J., Deutsch, C.V.: Geostatistical Reservoir Modeling, second ed. Oxford University Press, New York, USA. (2014)

Reinecker, J., Grobe, R., Hochschild, T., Bauer, J.F., Meier, S., Philipp, S.L., Filomena, M, Stollhofen, H., Bechstädt, T., Drews, T., Miernik, G., Soyk, D. and Melchert, B.: Verbundprojekt AuGE: Aufschlussanalogstudien und ihre Anwendbarkeit in der geothermischen Exploration – Entwicklung von Methoden zur Ermittlung von Permeabilitäten und Transmissivitäten aus Reservoir-Informationen des Oberrheingrabens - Schlussbericht Teilprojekt A –FKZ: 0325302A, 79p., (2015).

Ritter, O., Junge, A., and Dawes, G. J. K.: New equipment and processing for magnetotelluric remote reference observations. *Geophys. J. Int.*, **132**, (1998), 535-548.

Ritter, O., Tietze, K., Patzer, C. and Veeken, P.: Onshore 3D CSEM Inversion in Practice, *Proceedings*, 6th International Symposium on Three-Dimensional Electromagnetics, Berkeley, California, USA, March 28-30, (2017)

Rühaak, W., Guadagnini, A., Geiger, S., Bär, K., Gu, Y., Aretz, A., Homuth, S. and Sass, I.: Upscaling Thermal Conductivities of Sedimentary Formations for Geothermal Exploration. *Geothermics*, **58**, (2015), 49-61.

Sass, I. and Götz, A.E.: Geothermal reservoir characterization: a thermofacies concept. *Terra Nova*, **24(2)**, (2012) 142–147. DOI: 10.1111/j.1365-3121.2011.01048.x

Sass, I. and Hoppe, A.[Eds.]: Forschungs- und Entwicklungsprojekt 3D Modell der geothermischen Tiefenpotenziale von Hessen. *Abschlussbericht*, (2011), 218 p., Technische Universität Darmstadt.

Sass, I., Weinert, S. and Bär, K.: Success rates of petroleum and geothermal wells and their impact on the European geothermal industry. *Swiss Bull. Angew. Geol.* **21(2)**, (2016), 57-65, http://doi.org/10.5169/seals-658197.

Streich, R., Becken, M., Matzander, U. and Ritter, O.: Strategies for landbased controlled-source electromagnetic surveying in high-noise regions. *The Leading Edge*, **30(10)**, (2011), 1174–1181

Streich, R.: 3D finite-difference frequency-domain modeling of controlled-source electro-magnetic data: Direct solution and optimization for high accuracy. *Geophysics*, **74(5)**, (2009), F95–F105.

Streich, R. and Becken, M.: Electromagnetic fields generated by finite-length wire sources: comparison with point dipole solutions. *Geophysical Prospecting*, **59**, (2011), 361–374.

Streich, R., Becken, M. and Ritter, O.: Robust processing of noisy land-based controlled-source electro-magnetic data. *Geophysics*, **78(5)**, (2013), E237–E247

Streich, R.: Controlled-Source Electromagnetic Approaches for Hydrocarbon Exploration and Monitoring on Land. *Surveys in Geophysics*, **37(1)**, (2016), 47-80.

Schaller, A., Streich, R., Drijkoningen, G., Ritter, O. and Slob, E.: A land-based CSEM method for oil field exploration: An example from the Schoonebeek oil field, *Geophysics*, **83**, (2017), doi:10.1190/geo2017-0022.1.

Sippel, J., Fuchs, S., Cacace, M., Braatz, A., Kastner, O., Huenges, E., and Scheck-Wenderoth, M.: Deep 3D thermal modelling for the city of Berlin (Germany). *Environmental Earth Sciences*, **70 (8)**, (2013), 3545–3566.

Tietze, K., Ritter, O., and Veeken, P.: Controlled-source electromagnetic monitoring of reservoir oil saturation using a novel borehole-to surface configuration. *Geophysical Prospecting*, **63**, (2015), 1468_149

Tietze, K., Ritter, O., Patzer, C. and Veeken, P.: Borehole CSEM for HC-Saturation Monitoring in the Bockstedt Oilfield (Onshore NW Germany). SPE Reservoir Evaluation & Engineering-Formation Evaluation. (2017)

Tietze, K., Patzer, C., Ritter, O. Veeken, P. and Verboom, B.: CSEM for monitoring reservoir oil-saturation using a borehole-to-surface set-up. Society of Exploration Geophysicists International Exposition and 85th Annual Meeting, New Orleans, LA, USA, 18 - 23 October 2015. *Extended abstract*, Oral discussion / e-poster, (2015), 4 pp.

Vidal, J.; Genter, A. Overview of naturally permeable fractured reservoirs in the central and southern Upper Rhine Graben: Insights from geothermal wells. *Geothermics*, 74, (2018), 57–73.

Vogt, C., Mottaghy, D., Wolf, A., Rath, V., Pechnig, R., Clauser, C.: Reducing temperature uncertainties by stochastic geothermal reservoir modelling. *Geophys. J. Int.* **181 (1)**, (2010), 321–333.

Weckmann, U., Magunia, A. and Ritter, O.: Effective noise separation for magnetotelluric single site data processing using a frequency domain selection scheme, *Geophys. J. Int.*, **161, 3**, (2005), 456-468.

White, C.D., Willis, B.J., Narayanan, K., Dutton, S.P., 2001. Identifying and Estimating Significant Geologic Parameters with Experimental Design. *SPE Journal* **6 (03)**, 311–324.

Witter, J.B., Trainor-Guitton, W.J., Siler, D.L., 2019. Uncertainty and risk evaluation during the exploration stage of geothermal development: A review. *Geothermics* **78**, 233–242