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Assessment of Deep Geothermal Resources and Potentials with a Multi-Criteria Approach Based on Multi-Scale Datasets and Models

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ABSTRACT

Assessing resources of enhanced geothermal (EGS) or medium deep geothermal systems (MDGS) for direct heat use and underground thermal energy storage (UTES) is a challenging task where usually diverse data sets of multiple origin and scale have to be compiled to obtain a comprehensive conceptual model of the subsurface, its structure and its properties. Within the research project "Hessen 3D 2.0" (BMWI-FKZ: 0325944), which aims to enhance the assessment of the prospective risk (‚Fündigkeitsrisiko') for these kinds of geothermal projects, we established a workflow to implement and analyse such broad data sets.

In a first step, comprehensive datasets of physical rock-, fluid- and reservoir properties are compiled which are based on investigations on relevant reservoir analogues, hydraulic test data from boreholes and borehole geophysical logs. The second step comprises the development of 3D geological models from a combination of borehole data, geological cross sections, seismic profiles, gravity and geomagnetic anomalies and geological maps to achieve the required detail on subsurface structure. This is prerequisite to distinguish the potentially usable reservoir units both within the crystalline or metamorphic basement and the sedimentary cover. Geostatistical analysis of the acquired comprehensive geothermal database is performed in a third step of the workflow; this allows for a parametrization of the geological model, for thermohydraulic subsurface modelling, and finally for the geothermal resource assessment. Such models, which consider the variability of rock and reservoir and fluid properties provide a thorough understanding of the subsurface temperature distribution, the dominant heat transport processes and hydraulic conditions.

Finally, under consideration of both technical and economic boundary conditions and the statistics for the different relevant reservoir properties of the different geological units, assessment of hydrothermal, petrothermal and UTES potentials is performed directly with the 3D model. Therefore, a multiple-criteria approach, which assesses the quality of various rock and reservoir properties and their relevance for the different geothermal utilizations is implemented. This 3D-grid based method can be used for an identification and visualization of different geopotentials using various parameters to determine each potential. Thereby, to specify the grade of each potential under technical and economic requirements, threshold values for each parameter are defined.

The approach described here allows for a stochastic assessment of the geothermal resources of a particular site of interest, including the determination of the probability of success and it provides the necessary numbers to attract investors to geothermal projects.

1. INTRODUCTION

Due to the anthropogenic impact on global warming and urgent need to replace fossil fuels, renewable energies play the key role in the attempt to reduce greenhouse gas emissions as quickly as possible. The debate about alternative energy resources so far often focused on the supply of electricity, even though heating accounts for approximately 55 % of the annual final energy consumption in Germany (BMWi, 2017). Within the scope of the German ‚Energiewende', also potentials for storage of heat and power are becoming more and more important to allow for the implementation of volatile renewable energies. To reduce CO2-emmissions in the future, cutting-edge technologies are required. New combinations of renewable energies – e.g. solarthermics and geothermics – complemented by seasonal underground thermal energy storage (UTES) in aquifers or by shallow to medium deep borehole heat exchanger fields (e.g. Bär et al. 2015a,b, Welsch et al. 2018) are techniques with a huge potential.

Additionally, as opposed to other renewable energy sources, geothermal energy can be extracted regardless of the season, the time of day or the weather conditions. It can therefore be used to cover the base load, for both power and heat production depending on the extraction temperature. Over 95% of the deep geothermal potential for power production of Germany are located within the crystalline basement (TAB 2003). But so far in Germany, geothermal power and heat are only produced from hydrothermal systems, since both the techno-economic feasibility of enhanced geothermal systems (EGS) are not yet demonstrated and the current state of knowledge about the structure, composition, reservoir properties and long-term behavior of the basement is not yet sufficient.

1.1 The project Hessen 3D 2.0

For the Federal State of Hesse, so far no regional assessment of petrothermal or medium deep geothermal resources are available (in contrast to hydrothermal resource assessment). To close this gap, the main goal of the BMWi-funded project "Hessen 3D 2.0" is to enhance the assessment of the prospective risk (‚Fündigkeitsrisiko) for geothermal projects in Hesse. It is therefore intended to significantly increase the detail of the existing 3D geological models of Hessen (Arndt et al. 2011, Freymark et al. 2015) to be able to distinguish both the petrological units of the basement and the potential reservoir formations in the sedimentary cover in terms of their geothermal properties. This is further implemented in numeric simulations, namely in thermohydraulic models of the subsurface temperature distribution which consider the variation of rock and reservoir properties and the dominant heat transport processes. This physical-numerical approach should significantly increase the quality of any resource assessment compared to the predecessor project 'Hessen 3D' (Bär et al. 2011, Arndt et al. 2011, Bär and Sass 2014).

To achieve its goals, the "Hessen 3D 2.0" project is structured according to the general workflow presented in **Error! Reference source not found.** and consists of three subprojects focusing on the development and enhancement of (i) rock property databases (to characterize the rocks, fluids and reservoirs), and (ii) thermohydraulic subsurface models (for the geothermal resource assessment). The first subproject deals with the petrothermal potential prognosis of the crystalline and metamorphic basement rocks, while the second is focused on the potential for direct heat of and heat storage in the sedimentary cover; the third subproject will focus on the thermohydraulic modelling as described above. Additionally, the hydrochemistry and fluid properties of reservoir fluids are compiled in a special database.

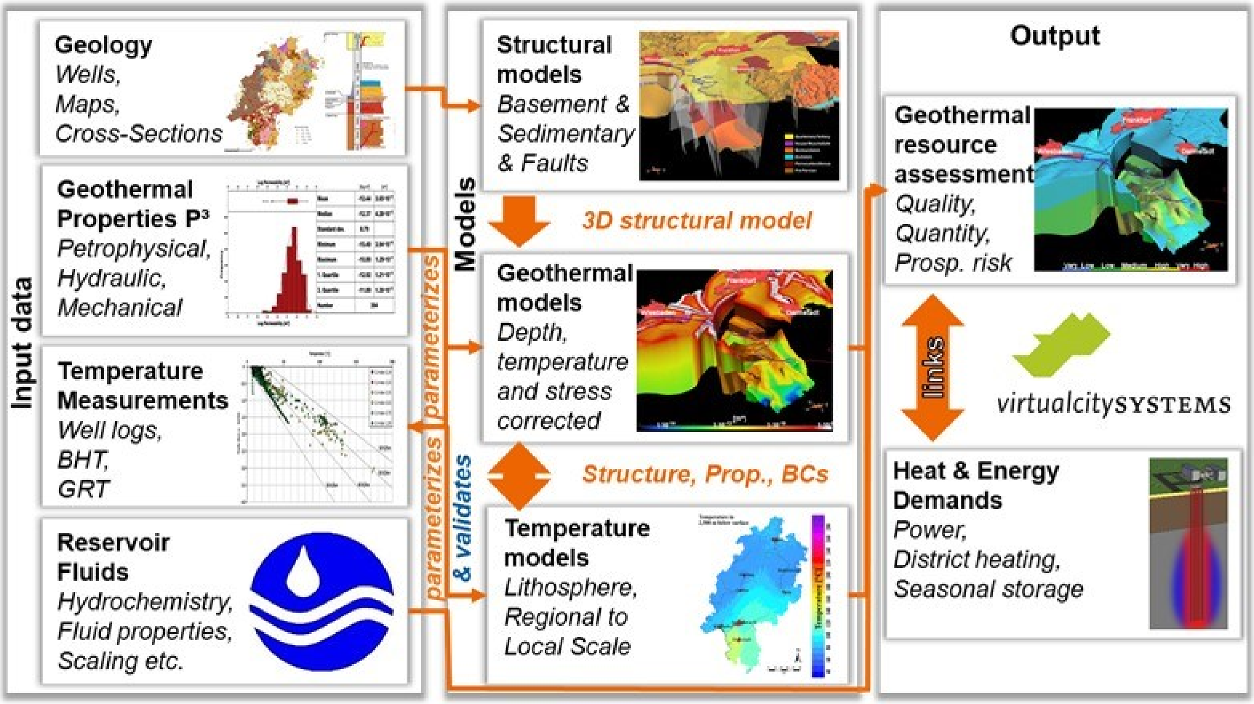

Figure 1: Workflow of the Hessen 3D 2.0 project from the four main tiers of input data (geology, geothermal properties, subsurface temperature and properties of reservoir fluids) to the 3D structural models to the 3D geothermal and subsurface temperature models resulting in an qualitative and quantitative assessment of geothermal resources eventually being linked to heat and energy demands and infrastructure. BCs – boundary conditions

The Federal State of Hesse in central Germany geologically covers parts of the North German Basin (north Hesse) and the European Cenozoic Rift System (south Hesse), both situated on top of three major basement units that are lithologically complex (and a product of the Variscan orogeny). As part of the active rift system, the Upper Rhine Graben is an area of geothermal exploration. The investigation of regional fluid flow and heat transport has been 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). In Hesse, 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. In particular, the effects of cold recharge and convective upflow of heated fluids on a regional scale (Schilling et al. 2013) need to be better quantified in order to predict geothermal potentials.

As described in Person et al. (1996), hydrological, thermal, chemical and mechanical mass transfer processes are closely coupled in groundwater flow systems in sedimentary basins. To assess how structural and geological heterogeneities influence deep heat transport and which dynamics need to be considered if predictions of temperature distributions and flow regimes are made for Hesse, a 3D representation of the subsurface structure and its physical properties is required. The heterogeneous geology of Hesse makes the area suitable to study the interaction of conductive, advective and free convective heat and fluid flow processes, as they are thought to simultaneously occur in the study area.

For the assessment of hydrothermal, petrothermal and UTES potentials, both technical and economic boundary conditions have to be considered and, of course, the statistics for the different reservoir properties. This allows for stochastic assessment of the potentials including the determination of the probability of success, which is one of the key requirements for risk insurance ('Fündigkeitsrisikoversicherungen') and provides the necessary numbers to attract investors to geothermal projects.

Eventually, the modelling results are planned to be coupled to existing 3D city models (e.g. Frankfurt a. M.) which document the local and regional heat demand and in combination with the geothermal potentials can lead to identify suitable locations for geothermal projects. Furthermore, the results will be published online and as open-access information so that project developers, planers, local or regional energy companies, government institutions as well as scientists can interactively access and use all provided information. Additionally, all results will be provided to the geothermal information system of Germany (GeotIS) hosted by the LIAG.

1.2 Geology of the study area

The Hessian geology is characterized by a diversity of geological domains. Pre-Permian metamorphic crust crops out in the north-west (Rhenohercynian) and crystalline crust in the south-east of Hesse (Saxothuringian, Mid-German-Crystalline High), whereas Mesozoic sediments reach up to 1.4 km thickness in the Hessian Depression (north), and Cenozoic to Paleozoic sediments more than 3.8 km in the Upper Rhine Graben (south). The infill of the Hessian Depression consists mainly of clastic fluvial-lacustrine sediments (Buntsandstein) with thicknesses increasing northward (Paul, 1999). In the Oligocene, the Hessian Depression and the Upper Rhine Graben are believed to have been connected (Berger et al. 2005a,b, Murawski et al. 1983). In contrast, the volcanic complex of the Vogelsberg mountains structurally and hydraulically separates the southern area of Hesse (mainly Upper Rhine Graben) from the northern Hessian Depression (Bogaard and Wörner 2003, Jung 1999, Sherwood 1990). The sedimentary series of southern Hesse can be differentiated into deposits of the Permian Saar-Nahe Basin and the Cenozoic deposits of the Upper Rhine Graben sedimentary infill (Dézes et al. 2004).

2. DETERMINING GEOTHERMAL ROCK AND RESERVOIR PROPERTIES

To predict geothermal properties for the entire subsurface of Hesse, a comprehensive measurement data set derived from outcrop analogue studies, boreholes and core investigations as well as hydraulic tests has been compiled for all relevant formations. Systematic laboratory measurements of thermophysical, hydraulic and mechanical rock properties were conducted on both oven-dry and water saturated samples for each sample, respectively. Thus a vast geothermal database has been created. Due to the large number of measurements, the database is ideal for statistical analysis of each parameter and correlation analysis between the different parameters.

2.1 Methodology

Laboratory analyses comprise thermophysical properties such as grain density, bulk density, porosity, thermal conductivity, thermal diffusivity, compressional and shear wave velocities and – at selected samples mainly from the crystalline and metamorphic basement – also rock mechanical properties such as unconfined compressive strength, confined compressive strength, poisson ratio, elastic moduli and tensile strength. All samples are dried to constant weight (at 105 or 60 °C depending on their clay mineral content). All measurements were conducted at laboratory conditions of an average atmospheric pressure of about 0.1 MPa and at 20 °C for thermal rock properties and at 23 °C for other petrophysical properties.

Grain density is determined with an accuracy of 0.02 % applying a gas expansion pycnometer (Micromeritics AccuPyc II 1340). Bulk density is measured in an envelope powder pycnometer (Micromeritics GeoPyc 1360, with an accuracy of 1.1 %) utilizing a well sorted, fine-grained powder as displacement material. Bulk volume, also analyzed in the powder pycnometer, bulk and grain density in combination allow to calculate the porosity of rock samples.

Bulk thermal conductivity and thermal diffusivity are measured in an optical thermal conductivity scanner (Lippmann and Rauen TCS) applying the optical scanning method after Popov et al. (1999). All measurements are conducted against a set of standards and with an accuracy of 3 % for the thermal conductivity and 5 % for the thermal diffusivity.

Specific heat capacities are calculated based on the measured thermal conductivity, bulk density and thermal diffusivity.

The measurement of intrinsic permeabilities is based on the principle of Klinkenberg (1941) using a column gas permeameter. The sample is mounted in a Hassler-cell and a gas pressure gradient is applied between the sample top and bottom surface (Filomena et al. 2014). Multiple single measurements under varying injection pressures at constant pressure gradients are used to extrapolate the intrinsic permeability applying the Klinkenberg-plot.

Ultrasound wave velocities are measured with a Geotron USG 40 ultrasound generator and two attached probes that enhance the shear wave signature. The sample is sandwiched between the two sensors and the contact is further enhanced by a shear gel (Magnaflux 54-T04) and a contact pressure of 0.1 MPa. Compressional and shear wave velocities are manually picked in graph of 16 stacked single analysis at 80 kHz.

The dynamic elastic parameters are calculated by

$$\nu_{dyn} = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)} \quad \text{and} \quad E_{dyn} = \rho_{bulk} v_p^2 \frac{(3V_p^2 - 4V_s^2)}{(V_p^2 - V_s^2)}$$

where ν_{dyn} is the dynamic Poisson coefficient, E_{dyn} is the dynamic Young's modulus, ρ_{bulk} is the bulk density and V_p and V_s are the compressional and shear wave velocity.

Uniaxial compressive strength, tensile strength, confined compressive strength, poisson ratio and elastic moduli were measured according to the standards of ASTM or ISRM.

2.2 Dataset of the Variscan Basement

Petrophysical and reservoir properties are analysed (a) to identify rock types that could be representative for the same model unit, (b) to parameterize the geological 3D-structural model accordingly and (c) to finally assess the subsurface variability in petrothermal potentials. Rock types thus are grouped together if they show comparable properties, while being separated into different model units if they show larger differences.

Although the petrothermal potential is modelled down to a depth of 6 km below sea level, due to a lack of deep cored wells the majority of the input data was measured on outcrop data from near the Earth's surface. Nonetheless, such outcrop analogue studies are a reliable way to estimate reservoir conditions. In case of basement rocks such as intrusive igneous rocks, hydraulic properties such as matrix permeability or porosity are, if unaltered conditions apply, negligibly low and often no depth correction needs to be applied. Hydraulic properties of these rocks are governed by the fracture network and fault zones (Stober and Bucher, 2007). For thermal properties such as thermal conductivity, thermal diffusivity or heat capacity, however, a stress and temperature correction to reservoir conditions is essential to characterize petrothermal systems. Such corrections can be derived from publications or existing laboratory data taken under various stress and temperature states (as presented by Zhao et al., 2016, or Vosteen and Schellschmidt, 2003).

The dataset acquired for the Variscan basement units finally comprises grain and bulk density, compressional and shear wave velocities, thermal conductivity and diffusivity, porosity as well as rock mechanical parameters such as unconfined and confined compressive strength, young's modulus, Poisson's ratio and tensile strength from more than 150 outcrop locations as well as from cores of three deep boreholes located in the northern Upper Rhine Graben representing samples from reservoir depth. More details are given in Weinert et al. (2020, this issue.).

2.3 Dataset of the Sedimentary Cover

In order to assess the hydrothermal potential of the Cenozoic units of the sedimentary infill of the northern Upper Rhine Graben, a collection of porosity and permeability data from more than 2500 core plugs of 16 oil and gas exploration wells with multiple core sections are available from the Geological Survey of Lower Saxony (Bär et al., 2013, Bär and Sass, 2015). This database also contains a petrographic classification. The samples used in this study are lithologically classified as claystone, siltstone, fine, medium and coarse sandstone as well as gravelly sandstone.

From the 16 wells with porosity and permeability measurements several cores were chosen for further analyses. From the existing core plugs 221 representing the potential reservoir units of the Pechelbronn-group and the Bunte Niederrödern layers were used for measurements of thermal conductivity and diffusivity and sonic wave velocity (p- and s-wave velocity), both under dry and saturated conditions. The selected core samples are representative for their lithofacies group and lithostratigraphic unit in terms of lithology, porosity and permeability. The cylinder-shaped samples were drilled perpendicular to the core axis, such that the sample axis is parallel to the bedding plane. They have a diameter of 30 mm and lengths of 25–50 mm. Additionally, gamma-ray logs of more 15 wells (by courtesy of Exxon Mobil) are used for correlation analysis with respect to lithology, porosity and permeability data. More details are given in Hintze et al. (2018).

2.3 Temperature data

The temperature database used to validate the simulated deep temperature fields originate from 467 boreholes, locally reaching depths of 3,314 m below surface (Upper Rhine Graben). These measurements were obtained using different measurement techniques (Rühaak et al. 2014). For 90% of the boreholes, temperature logs were measured, for 9% of the wells bottom hole temperatures are available and 1% of the measurements come from production tests. Most of the bottom hole temperature measurements are located in the Upper Rhine Graben and originate from hydrocarbon exploration boreholes. In total, 3642 temperature measurements could be used for temperature modeling and validation of modelled temperatures.

3. GEOLOGICAL 3D MODELLING

Geological 3D-structural models are the basis for our geothermal resource assessment including numerical thermohydraulic reservoir models. The structural 3D models for both the crystalline and metamorphic basement as well as for the sedimentary cover are built in SKUA-GOCAD©.

3.1 3D Model of the Variscan Basement

Based on the petrophysical characterization of reservoir analogues, generalized modelling units were predefined. As a first step of the 3D-modelling, available input data were evaluated to verify whether sufficiently valid input data are available to model the predefined units. In case of insufficient input data, the modelling unit is integrated into another modelling unit best fitting in terms of properties. This analysis leads to the definition of three major modelling units in the Mid-German Crystalline High: (1) granite and granodiorite, (2) gabbro and diorite, (3) metamorphic rocks. Although granite and granodiorite were dividable in their petrophysical properties, the input data of the 3D-model do not allow such a division in the regional-scaled approach. The proposed subdivision is further biased by decreased heat production rates of mafic rocks that locally occur within the mostly felsic host rock (Hasterok and Webb 2017) or by anisotropic mechanical properties of metamorphic rocks as opposed to rather isotropic properties of the crystalline rocks (e. g. Özbek et al. 2018).

The Northern Phyllite Zone is subdivided into (4) a southern zone of very low-grade metamorphosed sedimentary rocks (mostly very poorly exposed greywackes) and (5) a northern zone of low-grade metamorphosed rocks, mainly composed by phyllites.

In the Rhenohercynian zone, basically two units are modelled according to their mechanical behavior in the laboratory. Therefore, metamorphosed rock such as (6) metapelites are collected in a separate modelling unit and segregated from unmetamorphosed sedimentary rocks such as (7) greywackes or limestones. Input data allowed to increase the model resolution in the Taunus suture zone which is represented by the units of (8) Taunusquarzit, (9) Bunte Schiefer and (10) Graue Phyllite. In addition, the boundary towards the Northern Phyllite Zone is modelled in more detail. Low-grade metamorphic rocks are divided into (11) Lorsbacher

Schiefer, (12) Eppsteiner Schiefer and (13) metavolcanites. Increased model resolution in distinct areas was possible due to the publications of Klügel (1997) and Oncken (1989).

As input data for the geological 3D-structural model, the well database of the Hessian Agency for Nature Conservation, Environment and Geology, geological maps and cross sections, geophysical exploration data such as the DEKORP seismic lines or gravity and magnetic maps but also additional literature data (e.g Klügel 1997 and Oncken 1989) and a predecessor model (Arndt 2012) was compiled and integrated. The aim of the geological 3D-structural model is to provide a structural model down to 6 km depth below sea level.

Wells deeper than 20 m were considered and separated by their location in relation to the Variscan zones as well as drilled lithology. In total 198 wells were finally selected for the Mid-German Crystalline High, 232 wells for the Northern Phyllite zone and >400 wells in the Rhenoherzynian. Although deep wells are scarce and many of the selected wells are clustered in the basement outcrops, their location and lithological logs are applied to map spatial distribution of the defined modelling units in the near subsurface.

Model accuracy in greater depth is secured by mostly by geophysical input data such as the DEKORP reflection seismic lines DEK84-2S, DEK86-2N, DEK88-9N, DEK90-3A and DEK90-3B which further provide insight on the location of the boundaries of the Variscan zones. Additionally, geological cross sections of the general geological map of Federal Republic of Germany (1:200,000, Zitzmann 1994) were used. As shown for the Mid-German Crystalline High (Figure 2), major fault zones are modeled up to 6 km depth and with a dip, if available from e. g. seismic lines or published geological cross sections. Although not exposed, the northern boundary, namely the Northern Phyllite Zone, is also modelled as a listric deep fault zone striking in NE-SW direction. Their dip and location was extracted from the DEKORP seismic lines DEK84-2S and DEK90-3B and lithological logs within the margin area of the Northern Phyllite Zone and Mid-German Crystalline High.

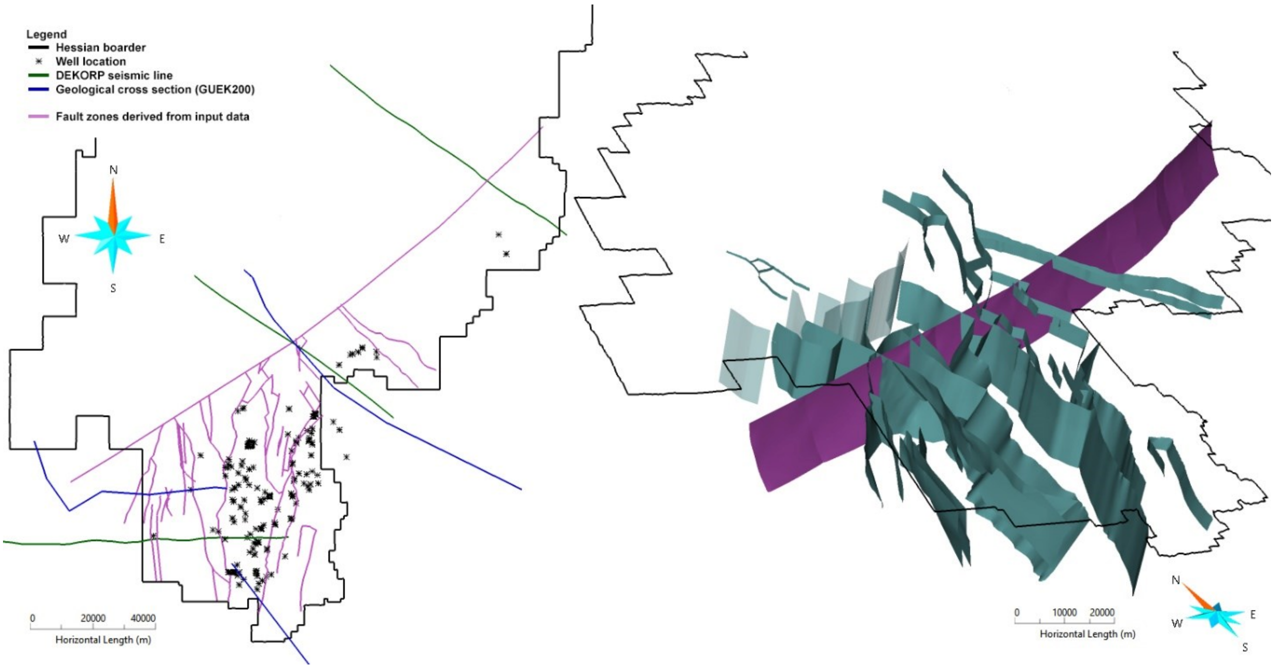

Figure 2: Selected input data such as well locations, DEKORP seismic lines and geological cross sections as well as derived fault zones (left) and 3D-modeled fault zones in SKUA/GOCAD (right), boundary fault of the Mid-German crystalline High and the Northern Phyllite Zone in lilac, other major fault zones in green.

3.2 3D Model of the Northern Upper Rhine Graben

The model of the Paleogene and Neogene fill in the northern Upper Rhine Graben comprises the following stratigraphic units from bottom to top: Pechelbronn-Group, Froidefontaine-Subgroup, Elsaß-Subgroup, Worms-Subgroup and Ried-Group (Grimm 2005). These horizons were modelled essentially based on borehole data and the DEKORP DEK88-9N seismic line. Input data for the faults are primarily structural maps (e.g. Perner 2018, Andres & Schad 1959, Illies 1974, Derer 2003) and seismic lines (Derer 2003). Where necessary, fault trace and geometry were adapted to borehole data. The model area and modelled horizons are shown in Figure 3. Due to the structural development of the Upper Rhine Graben, the number of modelled faults decreases to the top. For the Pechelbronn-Group more than 40 faults are modelled, the top horizon of the Ried-Group is only cut by three faults (major graben boundary faults not included).

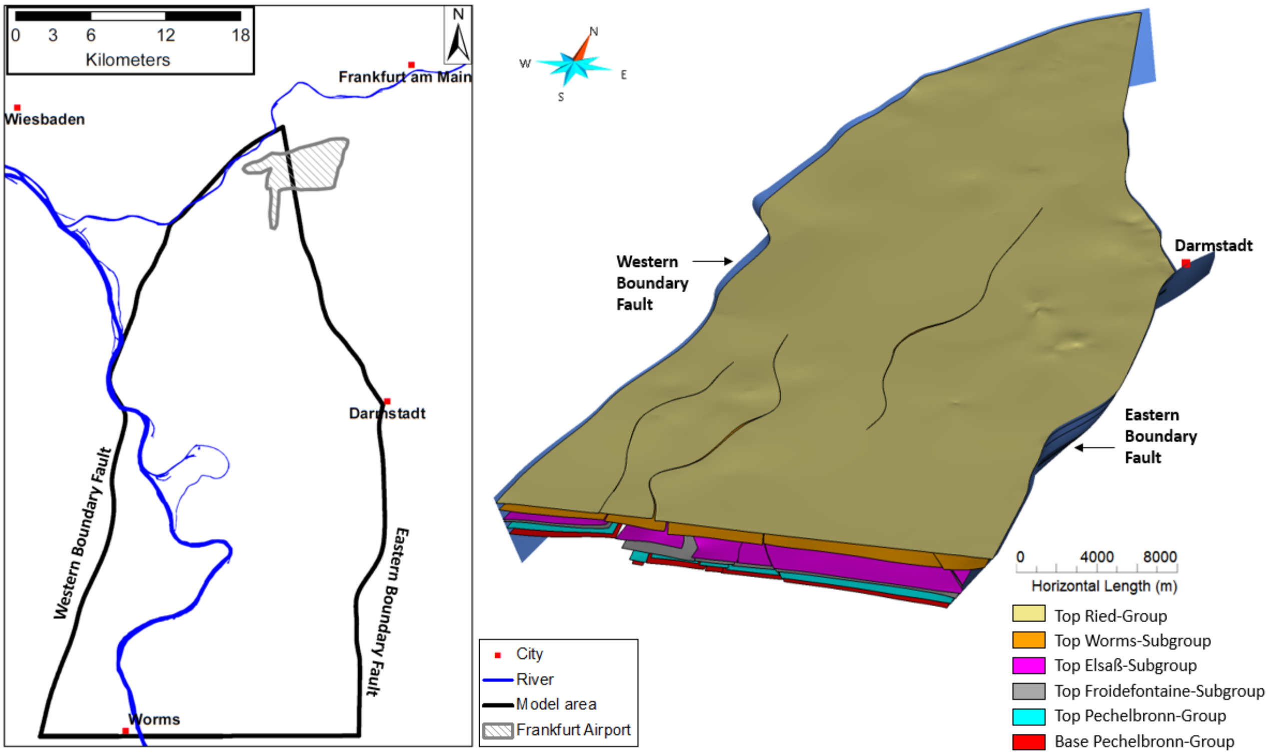

Figure 3: Model area of the 3D geological model of the northern Upper Rhine Graben (left) and modelled horizons with boundary faults (right).

4. MODELING THE THERMAL FIELD OF HESSE

Modelling of the thermal field in Hesse and of the governing heat transport processes in the subsurface has been approached in a three-step process: i) investigation of at first separately solved purely thermal and purely hydraulic processes in Hesse; ii) investigation of advective coupled processes and influence of hydraulic fluid flow on the deep thermal field of Hesse (Figure 4a) and iii) fully coupled transient simulations to investigate (additionally to conductive and advective heat transport) the free convective heat flow, i.e. the influence of the thermal field on hydrodynamics (Figure 4b-d)

Therefore, we used a detailed 3D structural model resolving six geological units (Variscan crust, Rotliegend, Zechstein, Buntsandstein, Zechstein and Cenozoic; after Arndt et al., 2011). Simulation results were later compared to temperature and hydraulic data as well as to hydrochemical investigations (for more detail see Koltzer et al., 2019). Based on these process simulations, we could subdivide Hesse into regions characterized by different governing heat transport mechanisms. In areas, where the Variscan crust crops out (Odenwald and Rhenish Massif), conduction is mainly controlling heat transport. In the northern model area, i.e. in the thick (up to 1.4 km) Buntsandstein reservoir (Hessian Depression) and at the eastern main border fault of the Upper Rhine Graben, cold meteoric water infiltrates into the sediments following high hydraulic gradients; as a result, colder temperatures are predicted by those simulations that implement advective heat transport (blue colours in Figure 4a,b). Finally, only in the northern Upper Rhine Graben (southern Hesse), where low hydraulic gradients, high thermal gradients and thick (up to 3.8 km) Cenozoic sediments interact for favourable conditions, the process of free convective flow is discernable from the models (Koltzer et al., 2019).

5. DATABASE OF HYDROCHEMISTRY OF RESERVOIR FLUID

Hydrochemistry and fluid properties of reservoir fluids are also an important component of geothermal resource assessment, since they significantly affect the amount of thermal energy stored in 1 m³ of thermal brine and additionally can be challenging for operation of a heat exchanger or power plant due to its scaling or corrosion potential.

The Federal State of Hesse is rich in thermal springs, some of which have been used for various purposes for centuries. But little effort is made to exploit these hydrothermal systems for heating purposes (Schäffer et al. 2018). One reason might be that the exploration of geothermal reservoirs and the assessment of underground properties is still a major challenge.

The establishment of a hydrochemical database on reservoir fluids provides parameters for the evaluation of hydrothermal systems. The data are derived from a comprehensive literature research in cooperation with the HLNUG and the BGR. Hydrochemical data sets from the Hessian territory that meet one of the following criteria and are not older than 1910 have been added to the database: i) water temperature at least 20 °C (definition thermal water); ii) solution content at least 1 g/l (definition mineral water); iii) depth at least 100 m (definition of the future formation water database of the BGR). The database contains thousands of data sets with metadata (coordinates, altitude, tapping type, etc.), references (analysis date, citation, etc.), physical parameters (like temperature, electrical conductivity, pH), chemical parameters (concentrations of ions and elements), sum parameters, dissolved and free gas contents, as well as isotope data. More details are given in Schäffer et al. (2019 in prep.).

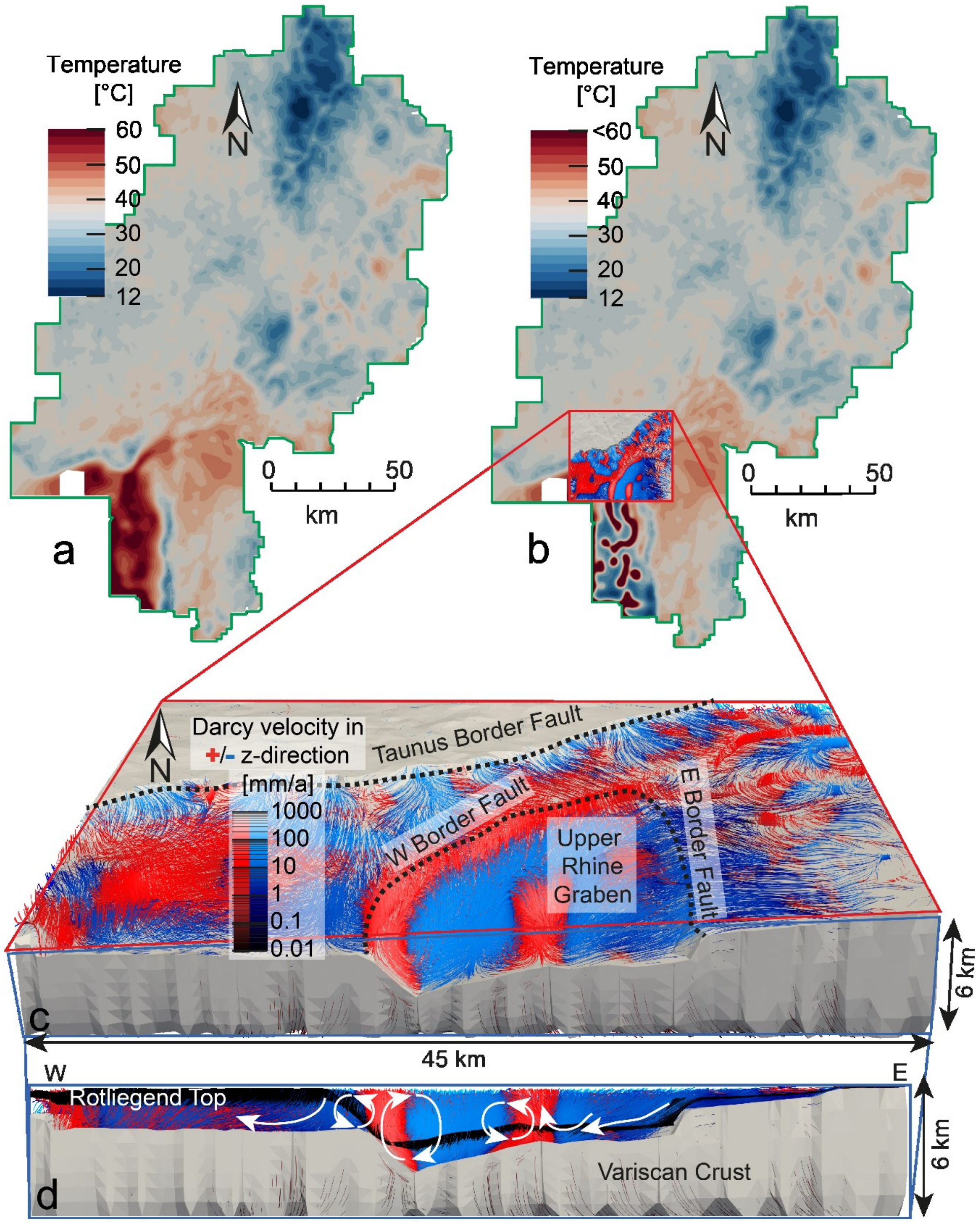

Figure 4: Simulation results from the coupled thermo-hydraulic model of Hesse. a) Temperature distribution at 1 km depth considering only advective and conductive heat flow; b-d) model results considering conduction, advection and free convection; b) temperature distribution at 1 km depth; c) stream lines in the northern Upper Rhine Graben; d) stream lines with interpreted convection cells (white arrows) in an W-E profile cutting the northern Upper Rhine Graben. In (a) and (b) from blue with cold temperatures to red hot temperatures and in (c) and (d) with blue colours downflow (negative z-component of the Darcy flow vector) and in red upflow zones. Figure modified after Koltzer et al., (2019).

In a first evaluation step, the database is used to assess the distribution and composition of mineral and thermal waters. The most important criteria for this are the water type (e.g. $Ca\text{-}HCO_3$ or $Na\text{-}Cl$ waters), the water temperature, the salinity, the CO_2 concentration and the depth of the tapping. In a second step, hydrothermal provinces are defined for Hesse and adjacent regions. Within a province, the water quality is similar, so it can be assumed that the genesis of the fluid is also similar. In a third step, the database contributes to the identification of hydrothermal potentials.

6. ASSESSMENT OF GEOTHERMAL RESOURCES

To analyse deep geothermal potentials two different approaches were combined. First steps of reservoir potential evaluation include the quantification of the heat in place following the simple volumetric approach of Muffler and Cataldi (1978) or more complex approaches ae introduced by e.g. Bundschuh and Suarez Arriaga (2010) In the second approach various rock and reservoir properties are assessed using a multiple criteria approach incorporating their relevance for the different geothermal systems. For this it is essential to identify relevant properties and bring them to a hierarchic weight, which is created by a pair wise comparison of the chosen parameters according to the very common multi criteria decision support system of the Analytic Hierarchy Process (AHP) introduced by Saaty (2005 and references therein). For detailed descriptions on the background of this newly developed method for geopotential evaluation with GOCAD see Arndt et al. (2011), Arndt (2012), Bär (2012) and Bär and Sass (2014 and 2015)

6.1 Assessment of petrothermal potentials

In general, the assessment of petrothermal potentials in our proposed approach is based on two columns (Figure 4). Firstly, a petrophysical database is fed with petrophysical properties, measured on either reservoir samples from deep wells or analogue outcrops. Secondly, a geological 3D-structural model is created, which resolution is dependent on the aimed scope. In the presented work, the resolution is focused on large fault zones and regional-scaled geological features such as the Variscan zones. The chosen resolution is due to the regional-scaled reservoir model of the hessian basement geology and fits to input data available for the model. Each modelling unit is represented by a SGrid generated of the geological 3D-structural model. SGrid cells are approx. 100x100x50 m, depending on the model resolution, model structure and geological features.

For each SGrid cell the heat in place H_0 is calculated with

$$H_0 = \int \left[(1-\varphi)c_r\rho_r(T - T_{ref}) + \varphi\rho_w\left(H_w(T) - H_w(T_{ref})\right)\right] dV$$

where φ is the porosity, c_r is the specific heat capacity of the rock, ρ_r is the rock density, ρ_w is the water density H_w specific enthalpy of water, V is the volume of the SGrid cell, T is the reservoir temperature and T_{ref} is the reference temperature or return temperature, respectively.

Estimated heat in place is further multiplied by a recovery factor

$$H = H_0 \cdot R$$

where H_0 is the heat in place and R is the recovery factor.

The recovery factor of geothermal systems is widely discussed (Gringarten 1978, Williams 2007, Grant and Garg 2012, Gholizadeh Doonechaly et al. 2016) but no conclusive data is published yet. Assumed recovery factors for petrothermal systems were estimated as high as 50-70 % (Williams 2010, Sanyal and Butler 2005) but also as less than 2 % (Grant and Garg 2012). Especially in petrothermal reservoirs, the fracture network, whether natural or artificial, contributes to the achievable recovery factor which can reach its maximum at a specific fracture permeability (Gholizadeh Doonechaly et al. 2016). Despite any assumptions for potential assessments, site specific data is required for more accurate estimations of recoverable heat.

A second petrothermal potential assessment is a qualitative assessment based on the petrophysical reservoir properties and interactively accessible in 3D space, directly in SKUA/GOCAD. Therefore, petrophyiscal properties are weighted regarding their importance in petrothermal systems and are assessed in an AHP. While matrix permeabilities and porosities are of lesser importance in petrothermal systems, thermal conductivity, thermal diffusivity and heat capacity are higher ranked. In addition, fracture propagation is estimated by the Perkins-Kern-Nordgren model (Perkins and Kern 1961, Nordgren 1972) based on elastic and rock mechanical properties such as Young's modulus. For more details see Weinert et al. (2019, this issue).

6.2 Assessment of hydrothermal potential for direct heat supply

The model units of the structural 3D model are parametrized with statistically evaluated measurement results of core samples. In regions with enough input data the density, porosity and permeability are statistically inter- and extrapolated with the SKUA/GOCAD Reservoir Modeling workflow (Paradigm 2013). The applied method is a sequential Gaussian simulation with a combined kriging method. Ordinary kriging is applied for density and porosity and collocated cokriging for permeability (with the modelled porosity as soft data). The specific heat capacity of the rock matrix is assumed to be constant. In order to account for the property variation, the 10th, 25th, 50th, 75th and 90th percentiles are used. With the modelled porosity values and the specific heat capacity of water (at 20 °C) the reservoir specific heat capacity (at 20 °C) is calculated for each cell using the geometric mean model. The reservoir temperature (adopted from Arndt et al. 2011) is then used to convert the specific heat capacity to reservoir conditions.

The heat in place (HIP) method (e.g. Muffler & Cataldi 1978, reformulated by Garc & Combs 2015) yields an overall estimate of the theoretically extractable heat (H_R) for each model unit:

$$H_R = V(\phi\rho_w c_w + (1-\phi)\rho_m c_m)(T_R - T_{ref}),$$

where V is the reservoir volume, Φ is the porosity, ρ_w and ρ_m are the densities of water and the rock matrix, respectively, c_w and c_m are the specific heat capacity of water and the rock matrix, respectively and T_R and T_{ref} are the reservoir and reference temperatures, respectively. The injection temperature serves as reference temperature. Yet, in order to account for heat losses, the theoretically extractable heat has to be multiplied by the recovery factor (r_f), thus yielding the actually usable heat (H).

6.3 Well-based resource assessment

The software tool DoubletCalc (van Wees et al. 2012) is used to assess the potential for direct heat production via doublets. Input parameters are aquifer properties, pump properties and well properties. For the latter two standard design parameters are assumed.

The well-based assessment of the hydrothermal potential will be carried out based on the same geothermal model parametrization. Parameters with the highest influence on the performance and efficiency of a hydrothermal doublet are according to Stober et al. (2016) the porosity, permeability, temperature and transmissibility. During inspection of the cores of the eight boreholes that were used for further analyses no indication of fractures in the potential reservoir could be observed. Neither do well log files mention any evidence of fractures. Hydraulic tests (if existing) are confidential and not available to the authors. According to Kött and Kracht (2010), the aquifer horizons within the Upper and Lower Pechelbronn Beds are porous aquifers. It is therefore assumed that fractures have no significant positive impact on reservoir permeability, which is thus considered to be in the same order of magnitude as the matrix permeability. This assumption might lead to an underestimation of the reservoir permeability and can thus be seen as a conservative estimate of the hydrothermal potential.

The geothermal power (P_{th}) extracted by the heat exchanger depends on the heat capacity of water (c_p), the temperature difference between production and injection (ΔT) and the mass flow (Q_m). Higher permeabilities and greater thicknesses yield higher flowrates. It is therefore convenient to use the transmissibility for the parametrization of the 3D model. It is commonly assumed that hydrothermal systems require a minimum transmissibility of $5 \cdot 10^{-12}$ m³ (Stober et al., 2016). For borehole locations where there is a detailed lithology log available, the relative thickness of each lithofacies group is known. The permeability data is evaluated separately for each lithofacies group. The transmissibility can then be calculated for each lithofacies group. As the thickness might vary considerably from one depocenter to another, the transmissibility cannot be interpolated over the whole study area, but only within fault blocks that display (semi)isolated depocenters and only if enough data is available. The inter- and extrapolation in areas without available borehole data implicate higher uncertainties.

For the injection temperature three scenarios are assumed: 90 °C for power generation with binary power plants, 50 °C for direct heat production and 30 °C for greenhouse farming. For a given pressure difference between production and injection well (e.g. 1, 3 and 6 MPa) the flow rate can be calculated as following (after Van Wees et al., 2012, Mijnlieff et al., 2014), where Q_v is the volumetric flow rate, ρ is the brine density, Δp is the pressure difference between the initial hydrostatic pressure in the aquifer and the well pressure, K_i is the permeability of the lithofacies groups (that are used for the water extraction and injection), H_i is the thickness of these permeable layers, μ is the dynamic viscosity, L is the well distance, r_{out} the outer well radius and S the skin factor (the skin factor could be used to account for deviated wells (Mijnlieff et al., 2014)).

$$Q_v = \frac{Q_m}{\rho} = \Delta p \, \frac{2\pi \sum_1^n K_i H_i}{\mu\left(\ln\left(\frac{L}{r_{out}}\right) + S\right)}$$

With known flow rate the geothermal power can be calculated. Here a maximum threshold for the drawdown needs to be included to ensure economic production.

The assessment of the hydrothermal potential will account for uncertainties by using the upper and lower end of the parameter ranges (e.g. Q90/Q75 and Q10/Q25) as well as the median values, resulting in an optimistic, a conservative and a realistic estimation, respectively. This statistical approach also allows for the calculation of the probability of occurrence to reach a certain geothermal potential.

7. CONCLUSION AND OUTLOOK

Compared to previous approaches of geothermal resource assessment of the federal state of Hesse we have:

1. Enlarged the database of rock, reservoir and fluid properties through multi-scale outcrop analogue investigations, laboratory analyses of petrophysical and fluid properties, well test analysis and well log analysis,
2. Enhanced the detail of structural 3D-geological models and defined additional model units both for the crystalline and metamorphic basement as well as for the Mesozoic to Cenozoic sedimentary cover,
3. Parameterized the model units by statistical analysis of the multiscale reservoir and fluid property dataset to set up geothermal models for resource assessment and thermohydraulic simulation of the subsurface temperature distribution,

The next steps will comprise:

I. Updating the coupled thermohydraulic models of the subsurface temperature distribution using the more detailed models and the updated rock, reservoir and fluid properties of the different model units,
II. The quantification and qualitative assessment of the petrothermal resources as well as of the potentials for UTEs and direct thermal use of the different model units including stochastic parameter variation,
III. Linking the resource assessment results to surface heat and power demand and to sources of seasonal excess heat for UTES by setting up 3D virtual models which are open-access for all stakeholders.

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