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# Quantification and Classification of Petrothermal Potentials: An Exploration Scheme for Mid-German Crystalline High Basement Rocks

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## ABSTRACT

A temperature higher than 100°C is a key requirement for geothermal power production. In many geotectonic settings, reservoir temperatures exceeding 100 °C is typically found in reservoir systems deeper than 3 km. Hydrothermal systems reach such temperatures in special geotectonic settings, e.g. in Graben systems as the Upper Rhine Graben or large-scale sedimentary basins as the Molasse basin in Germany, and are usually already under exploration and exploitation. Besides these easy to access hydrothermal systems, the majority of the geothermal potential is associated to petrothermal systems in crystalline or metamorphic basement rocks. However, to locate and quantify these petrothermal potentials is still a challenging task.

We propose an exploration scheme for petrothermal potentials, which is applied to the crystalline basement of the Mid-German Crystalline High as part of the European Variscan basement. The exploration is composed of three tiers: i) an outcrop analogue study, ii) a conceptual geological 3D-structural model and iii) the estimation of petrothermal potentials based on the comprehensive geothermal 3D-model composed as result of the first two tiers.

Petrothermal potentials are classified based on a custom-made weighting matrix based on multi-criteria analysis. Thermophysical rock properties such as thermal conductivity and thermal diffusivity as well as petrophysical rock properties including porosity, grain and bulk density or compressional wave velocities are assessed by this weighting matrix. Reservoir geometry, rock mechanical and structural geological data are fed into the weighting matrix as additional criteria to define the potential. Petrothermal potentials will be quantified by the volumetric method and assumption of recovery factors as experienced by current enhanced geothermal system (EGS) projects.

Necessary stimulation processes during reservoir development are considered by the implementation of rock mechanical properties and the recent stress field. By interlinking the latter ones and the implementation of fracture progression models, an estimation of resulting fracture dimensions can be performed. It is further intended to validate permeability evolution during fracture growth by hydro-mechanically coupled triaxial tests of various fractured crystalline samples.

## 1. INTRODUCTION

Geothermal systems provide a renewable energy source applicable for energy storage, heat production as well as power production. Further, geothermal energy is capable to provide base-load power which renewable energies such as wind or solar power lack.

In the past, reservoir types were commonly subdivided regarding their temperature (Muffler and Cataldi 1978; Hochstein 1988, 1990; Sanyal 2005), depth (Stober et al. 2016), reservoir permeability (e. g. Breede et al. 2015) or specific exergy (Lee 2001). Reservoirs characterized by natural permeabilities, either due to permeable faults or effective porosity, capable to supply sustainable discharge rates at the production well are referred to as hydrothermal systems. Such hydrothermal systems are already under operation in e. g. Germany (Molasse basin, Seithel et al. 2015), New Zealand (Rowland and Sibson 2004), USA (Elders et al. 2014) and many other locations worldwide. Research sites on tight sedimentary systems such as Groß Schönebeck (Germany, Legarth et al. 2003, 2005) are operational for research purposes.

Insufficient natural reservoir permeabilities may be enhanced by hydraulic stimulation (EGS) and such systems are often referred to as petrothermal reservoirs or systems. Although it is believed that the majority of geothermal potential is associated with petrothermal systems, the worldwide application of such systems is still restricted to few research sites like Soultz-sous-Forêts (France, Charléty et al 2006, Gerard et al. 2006, Sausse et al. 2006, Villeneuve et al. 2018) or abandoned projects such as Bad Urach (Germany, Plenefisch et al. 2015). Since high temperatures (> 100 °C) required for geothermal power production can often only be found in depth deeper than 3 km or more the development costs of geothermal power plants are increased significantly for petrothermal projects.

Although these high financial risks could be limited by exploration techniques such as slim hole exploration wells (Garg and Combs 1993), these exploration techniques are often neglected since they also require additional investments before an actual producing well doublet is drilled. Therefore, a profound understanding of the subsurface and its resources is required and it is necessary to limit exploration risks but also to identify and map new possible reservoirs.

For the case study of the crystalline basement of the federal state of Hesse (Germany) a newly developed exploration scheme for petrothermal potentials is demonstrated. Contrary to methods developed by e. g. Beardsmore et al. (2010), the proposed exploration scheme is based on an actual geological 3D-structural model of the area of interest, reflecting the current state of knowledge in as much detail as possible with the existing and freely available input data. The potential is not only estimated for large cells (e. g. c. 9×9 km cells, Beardsmore et al. 2010) but for volumes as small as 100×100×50 m. Furthermore, the calculation of the theoretical potential is not only based on thermal properties and rock's density but also additional petrophysical properties such as compressive and shear wave velocities and rock mechanical parameters are considered. Structural properties, such as major fault zones are considered as well, depending on the resolution of the 3D-structural model.

## 2. GEOLOGICAL OVERVIEW

The Mid-German Crystalline High (MGCH) strikes in NE-SW direction and extends over approx. 50-65 km width from northwest to southeast and several hundred kilometer length in NE-SW direction. The complex geology of the Mid-German Crystalline High is locally exposed in e. g. the Odenwald, Spessart as well as Ruhla Mountains (Figure 1) and hence well represented in SE Hesse and its vicinity.

The metamorphic and crystalline complexes are interpreted as the northern margin of Armorica (McCann et al 2008), a suture of the Rheic Ocean at the rim of the Bohemian Massif (Linnemann et al. 2008) and are fault-bounded to the Saxothuringian zone (Linnemann et al. 2008) to the SE. Towards NW, the MGCH is delimited by the Northern Phyllite Zone, but the boundary is not exposed or identified by wells yet. Although the contact area between the Northern Phyllite Zone and the MGCH is not exposed, a lithological change can be assumed by exploration wells in its vicinity and geophysical exploration such as the DEKORP seismic lines crossing the contact zone.

In outcrops of the MGCH, a variety of high-grade metamorphic Late Ordovician to Early Devonian rocks are exposed in the Böllsteiner Odenwald (450 Ma, Reischmann et al. 2001), Spessart Crystalline Complex (418-407 Ma, Lippolt 1986, Dombrowski et al. 1995) or the Ruhla Crystalline Complex (413-400 Ma, Brätz 2000, Zeh and Wunderlich 2003). Plutonic complexes within the MGCH are comprised by a variety of mafic, intermediate and acid rocks preferentially exposed in the Bergsträsser Odenwald, Spessart and Ruhla mountains. The Frankenstein Complex (northern Odenwald) is predominantly comprised by Late Devonian gabbro (362±7 Ma, Kirsch et al 1988) and metamorphic rocks. The southern part is composed by amphibolite-facies metamorphosed metasediments and gneiss (342-332 Ma, Todt et al 1995) which were intruded by the undeformed Weschnitz, Tromm and Heidelberg plutons. Referring to Timmerman (2008) all plutons are homogeneous and comprised by monzodiorite to granodiorite (Weschnitz pluton), granite (Tromm pluton) and gabbro to diorite with later granite and granodiorite intrusion at the Heidelberg pluton. Post-tectonic carboniferous diorite and granodiorite are dominantly exposed in the SE part of the Spessart Crystalline complex (c. 330 Ma, Anthes and Reischmann 2001). Carboniferous granites are the predominant crystalline rocks in the Ruhla mountains (Timmerman et al. 2008).

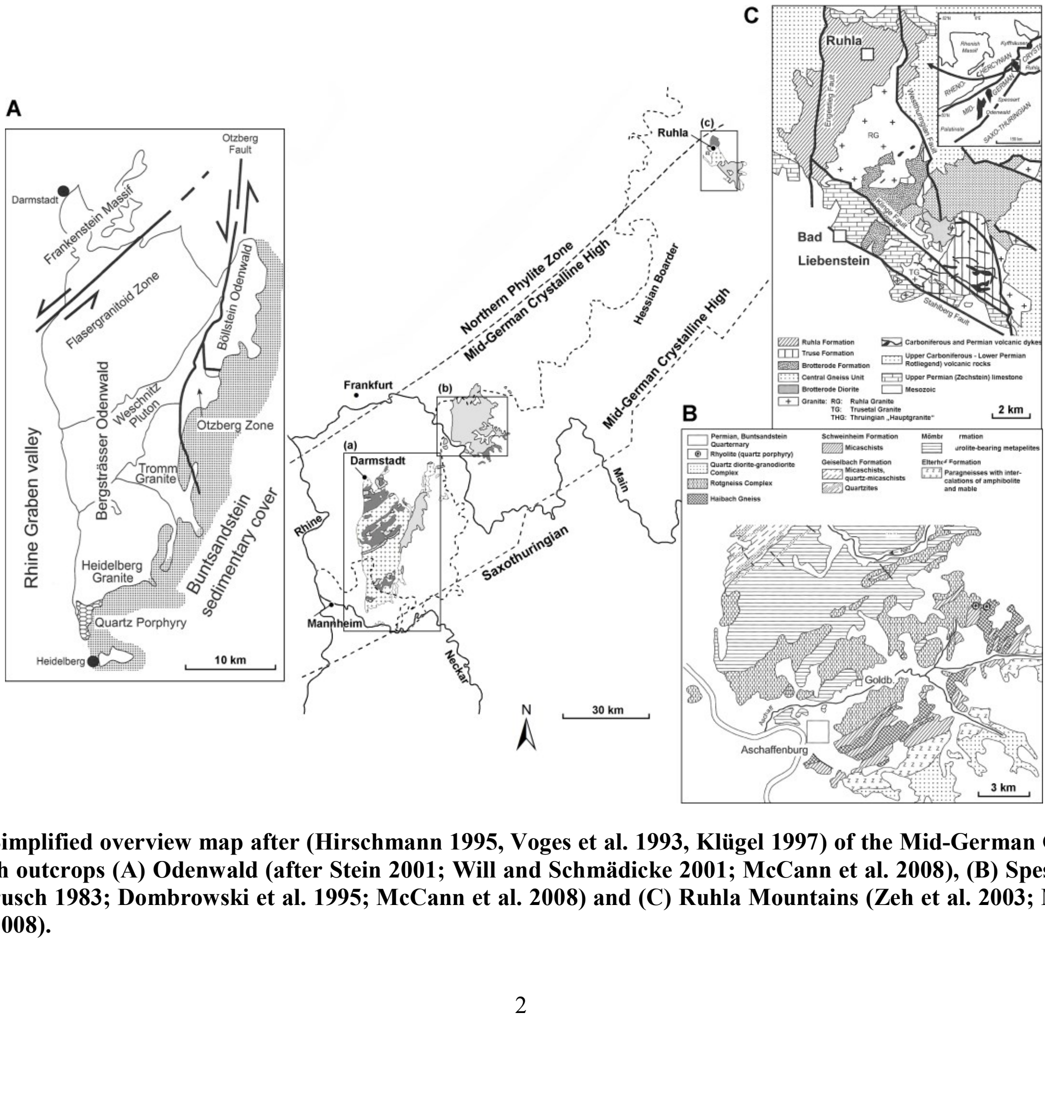


**Figure 1: Simplified overview map after (Hirschmann 1995, Voges et al. 1993, Klügel 1997) of the Mid-German Crystalline High outcrops (A) Odenwald (after Stein 2001; Will and Schmädicke 2001; McCann et al. 2008), (B) Spessart (after Okrusch 1983; Dombrowski et al. 1995; McCann et al. 2008) and (C) Ruhla Mountains (Zeh et al. 2003; McCann et al. 2008).**

## 3. OUTCROP ANALOGUE STUDY

Suitable sample material of deep and cored wells is scarce and often limited to few locations. To overcome this limitation, outcrops representing the assumed reservoir lithology can be selected and sampled instead. Additionally, in outcrops commonly greater quantities can be sampled to measure thermophysical as well as rock mechanical properties on the same large specimen. Nonetheless, such outcrop analogue studies are constrained by the spatial distribution of representative sampling locations.

In our study, sample material was derived from the crystalline Odenwald, Spessart as well as Ruhla mountains. Preferentially, the sample material was gathered from freshly excavated boulders in active quarries or unaltered, unweathered areas of inactive quarries or outcrops. If possible, boulders providing enough material for both, thermophysical and rock mechanical analysis were taken. Plugs of 40 mm diameter and 30 mm length were prepared for thermophysical properties and cores of 64 mm diameter at a length to diameter ratio of 2:1 were prepared for rock mechanical analysis. Tensile strength is analyzed on 64 mm diameter disks with a length to diameter ratio of 1:2.

Rock properties were measured on samples of more than160 locations distributed over the Spessart, Odenwald, Ruhla mountains as well as few wells and outcrops in the Palatinate Forest.

### 3.1 Methodology

Analysis included measuring thermophysical and petrophysical properties such as grain density, bulk density, porosity, thermal conductivity, thermal diffusivity, compressional and shear wave velocities and rock mechanical properties such as unconfined compressive strength, confined compressive strength and tensile strength at selected locations. All samples are dried until constant weight at 105 or 60 °C depending on their clay mineral content. All measurements are 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 % (Micromeritics 2013) applying a gas expansion pycnometer (AccuPyc II 1340). Bulk density is measured with an envelope powder pycnometer (GeoPyc 1360) utilizing a well sorted, fine-grained powder as displacement material. Bulk volume, also analyzed in the powder pycnometer, bulk and grain density allows to calculate the sample's porosity. The accuracy of the powder pycnometer is stated to be within 1.1 % (Micromeritics 1998).

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, 2016). All measurements are against a set of standards and with an accuracy of 3 % for the thermal conductivity and 5 % for the thermal diffusivity (Lippmann and Rauen 2013).

Specific heat capacities were calculated based on the following equation (Buntebarth 1989).

$$c_p = \frac{\lambda}{\rho_{bulk} \cdot \kappa} \tag{1}$$

where $c_p$ is the specific heat capacity, $\lambda$ is the thermal conductivity, $\rho_{bulk}$ is the bulk density and $\kappa$ the 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.

Dynamic elastic parameters are calculated by

$$\nu_{dyn} = \frac{V_p^2 - 2V_s^2}{2\left(V_p^2 - V_s^2\right)} \tag{2}$$

$$E_{dyn} = \rho_{bulk} v_p^2 \frac{\left(3V_p^2 - 4V_s^2\right)}{\left(V_p^2 - V_s^2\right)} \tag{3}$$

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

### 3.1 Data Analysis

Data from the petrophysical analysis are taken to (a) identify rock types within the dataset with similar properties and (b) parameterize the geological 3D-structural model and (c) hence for the calculation of the petrothermal potential. Rock types with comparable properties are grouped to predefine modelling units in the geological 3D-structural model.

The dataset 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. As shown in Figure 2, rock types sampled in the MGCH can best be divided by thermophysical properties such as grain density and bulk density. Granites and granodiorites are dividable by grain density and can also be separated from diorites and gabbros. Although granites and granodiorites are dividable in their density, thermal properties such as thermal conductivity and thermal diffusivity do not allow such a distinct separation. Nonetheless, in thermal properties, diorite and gabbro can, as for density, be separated from granite and granodiorite. Metamorphic rocks always displayed highly varying petrophysical properties due to their inhomogeneity and anisotropy.

Based on the thermophysical properties, four predefined modelling units can be identified und subdivided in: (1) granite, (2) granodiorite, (3) gabbro and diorite and (4) gneiss or metamorphic rocks, respectively.

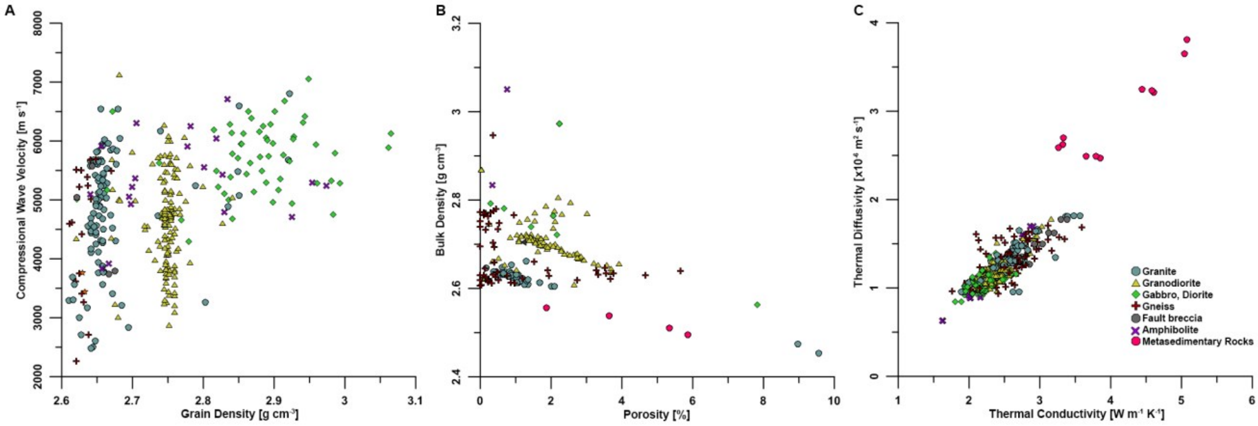


**Figure 2: Cross-correlation plots of (A) compressional wave velocity vs. grain density, (B) bulk density vs. porosity and (C) thermal diffusivity vs. thermal conductivity of selected measurements of Mid-German Crystalline High outcrop analogue samples.**

## 4. GEOLOGICAL 3D-MODEL

The geological 3D-Structural model is the basis of the petrothermal potential assessment. Based on the petrophysical characterization of reservoir analogue samples modelling units were predefined. As a first step of the 3D-modelling, available input data were evaluated to verify whether enough valid input data is available to model the predefined units. In case of insufficient input data, the modelling unit is integrated into the best fitting modelling unit leading to 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 division in the regional-scaled approach. The proposed subdivision is further influenced by decreased heat production rates in mafic rocks (Hasterok and Webb 2017) or anisotropic mechanical properties in metamorphic but rather isotropic behavior in crystalline rocks (e. g. Özbek et al. 2018).

As input data for the geological 3D-structural model, the well database of the Hessian Agency for Nature Conservation, Environment and Geology (HLNUG), geological maps and cross sections, geophysical exploration data such as the DEKORP seismic lines or gravity and magnetic maps but also additional literature data and a predecessor model (Arndt et al. 2011) was provided and integrated. The aim of the geological 3D-structural model is to provide a structural model between 400 m below surface and up to 6 km depth below sea level.

Well logs of 198 wells deeper than 20 m were selected, digitized and their well location and stratigraphic logs imported in SKUA/GOCAD. The DEKORP seismic lines DEK84-2S, DEK88-9N and DEK90-3B (Figure 3) were used to delineate the boundary towards the Northern Phyllite Zone, the orientation of major fault systems as well as lithological changes in depth up to 6 km below sea level. Additionally, geological cross sections of the general geological map of Federal Republic of Germany (1:200,000, Zitzmann 1994) were used. As shown in Figure 3, major fault zones are modeled down to 6 km depth and with correct dip angles as obtained from e. g. seismic lines or 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.

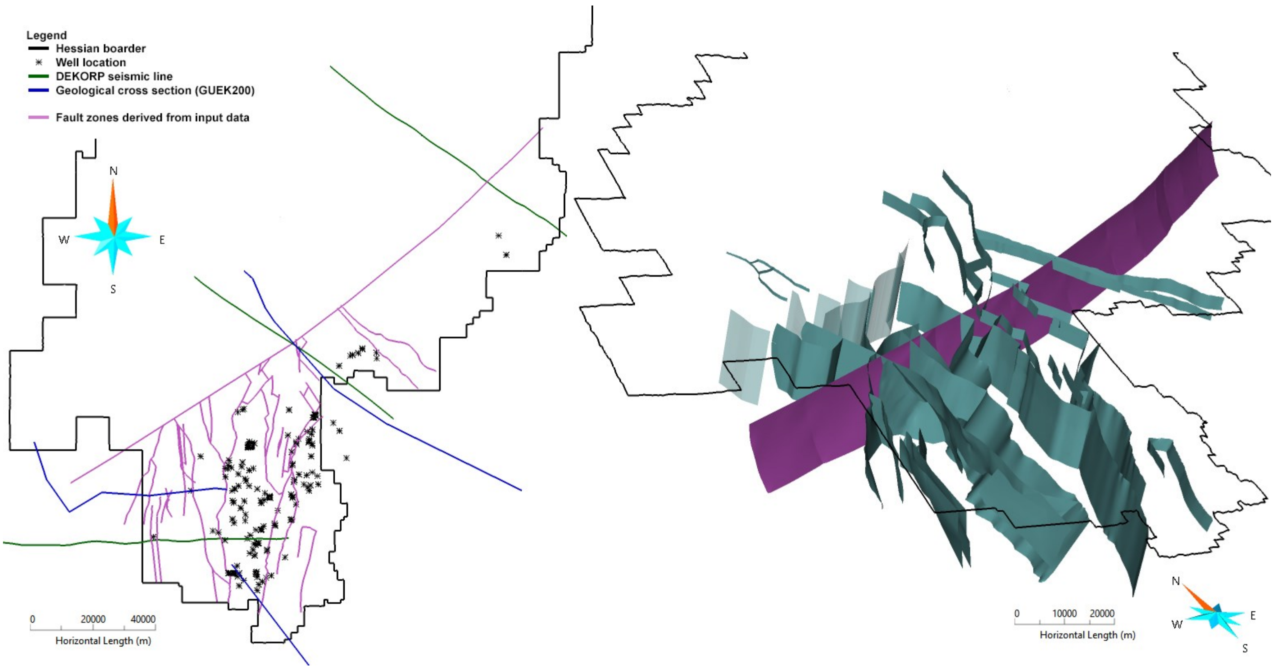


**Figure 3: Selected input data such as well locations, DEKORP seismic lines and geological cross sections as well as derived fault zones (left) and 3D-modeled fault zones (green) as well as the southern boundary of the Northern Phyllite Zone (violet) in SKUA/GOCAD (right).**

## 5. ASSESSMENT OF PETROTHERMAL POTENTIAL

In general, the assessment of petrothermal potentials in our proposed approach is based on two columns. 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 and available input data. 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 fit 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 after Muffler and Cataldi (1978) as

$$H_0 = \int \left[(1-\varphi)c_r\rho_r\left(T-T_{ref}\right) + \varphi\rho_w\left(H_w(T) - H_w\left(T_{ref}\right)\right)\right] dV \quad (4)$$

where $\varphi$ is the porosity, $c_r$ is the specific heat capacity of the rock, $\rho_r$ is the rock density, $\rho_w$ 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.

Following Jung et al. (2002) the estimated heat in place is further multiplied by a recovery factor

$$H = H_0 \cdot R \quad (5)$$

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 low as 2 % (Grant and Garg 2012). Especially in petrothermal reservoirs, the fracture network, wether natural or artificial, contributes to the achievable recovery factor which can reach its maximum at a specific fracture permeability (Gholizadeh Doonechaly et al. 2016). Note that fracture network not only controls heat exchange capacity of petrothermal systems but also controls the fluid flow (Genter et al 2010), permeability enhancement in hydraulic stimulation, influences the in situ stress (Afshari Moein et al. 2018a) and maximum magnitude of induced microseismicity in hydraulic stimulation (Afshari Moein et al. 2018b)). Despite any assumptions for potential assessments, site specific data is required for more accurate estimations of recoverable heat, which of course is only available after the first geothermal project in the respective geological setting has started production.

A second petrothermal potential assessment is a qualitative assessment following Bär et al. (2011), Bär and Sass (2014) and Arndt et al. (2011) based on the petrophysical reservoir properties and displayable in 3D space, directly in SKUA/GOCAD. Therefore, petrophysical properties are weighted regarding their importance in petrothermal systems and are assessed in an analytical hierarchy process (Saaty 2005). While matrix permeabilities and porosities are of less imporance in petrothermal systems, thermal conductivity, thermal diffusivity and heat capacity are ranked higher. Based on general assumptions for plutonic rocks, fracture length and height can be estimated by the Perkins-Kern-Nordgren model (PKN, Perkins and Kern 1961, Nordgren 1972) or Kristianovich-Geertsma-de Klerk model (KGD, Khristianovitch and Zheltov 1955; Geertsma and de Klerk 1969). Although elastic and rock mechanical properties such as Young's modulus as well as hydraulic stimulation data are needed to calculate fracture geometries, for a regional-scaled assessment, petrophysical as measured in our proposed workflow and hydraulic stimualtion data of comparable reservoirs (e. g. Soultz-sous-Forêts; Schill et al. 2017) can be applied.

Reservoir permeability is of high interest, for example for an estimation of the revovery factor as previously described, but also to achieve sufficient discharge rates at the well head. Although fracture permeabilities can be estimated by e. g. the combination of Darcy's and Poiseuille's Laws, often only intrinsic fracture permeabilities are calculated which do not represent realistic reservoir permeabilities (Lyons et al. 2016).

For a better understanding of fracture permeabilitiy, triaxial experiments are planned to measure the fracture permeability under different temperature and stress conditions in a thermo-triaxial testing device (Pei et al. 2015). Eventually, realistic values for fracture permeability of a certain reservoir can only be derived based on hydraulic tests, which can only be performed in the first well reaching the reservoir at target depth.

## 6. CONCLUSION AND OUTLOOK

As shown in this study, petrothermal potentials on a regional scale can be assessed based on the three-tiered approach combining an outcrop analogue study, a geological 3D-structural model and the 3D-model based estimation of petrothermal potentials based on the latter two.

The outcrop analogue study is primarily applied to generate a database of petrophysical properties. Predefined modelling units are derived from the petrophysical database and correlated and adapted to the input data available for the geological 3D-structural model. Additionally, petrophysical data is used for the parameterization of the SGrids derived from the 3D-model and thereby directly used for the assessment of petrothermal potentials.

The geological 3D-structural model is, in our case, a regional scale model considering the Mid-German-Crystalline High in Hesse and its close surroundings. The 3D model is based on input data of geological maps, geophysical exploration and lithological logs of the well database of the Hessian Agency for Nature Conservation, Environment and Geology (HLNUG).

To assess the petrothermal potentials, SGrids derived from the 3D-model are used. Cell sizes of the SGrids vary in dependency of the model resolution and structure but are commonly approx. 100×100×50 m in size. Each cell is parameterized with thermophysical and rock mechanical properties used for the assessment. Reservoir temperatures are derived from a predecessor model and also input data for the assessment of petrothermal potentials in depth of up to 6 km. The heat in place is calculated for each cell as well as the qualitative petrothermal potential based on an analytic hierarchy process.

In the near future, experiments of the permeability evolution are intended to validate the permeability evolution in fractures and during fracture growth. These experiments are planned to be conducted under different temperature and stress conditions.

## 7. ACKNOWLEDGEMENT

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