Investigation of the deep geothermal potentials of Hesse (Germany)

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ABSTRACT

Within the scope of the research project "3D-modelling of the deep geothermal potentials of Hesse" the deep geothermal potential of the Federal State of Hesse was assessed in a comprehensive approach. The heat in place has been quantified and the deep geothermal potentials were analyzed for different geothermal systems, as hydrothermal and petrothermal systems as well as fault related and closed systems like deep borehole heat exchangers.

For the assessment of the deep geothermal potential, knowledge of the geological structure and the geothermal properties of the potential reservoir rocks are indispensable. Therefore, a 3D geological structural model of the Federal State of Hesse (Germany) has been developed (Arndt 2012). For the assessment of deep geothermal potentials, the reservoir temperature is the key parameter. Therefore, the temperature distribution in the subsurface was modelled to a depth of 6 km below surface using actual data measured in deep wells. This model allows the prognosis of the underground temperature with a depth dependent accuracy of ±5 K ± 5 K/km.

Predictions of the geothermal properties are based on data sets of outcrop analogue studies, borehole data and core investigations as well as hydraulic test data compiled within the scope of this study. Systematic measurements of thermophysical and hydraulic rock properties such as thermal conductivity, thermal diffusivity, heat capacity, density, porosity and permeability of relevant geologic formations have been combined with in situ temperature measurements, hydrothermal upwelling zones, characteristics of geological faults in different lithologies and were added to the 3D geological structural model. Since both the hydraulic and thermophysical properties strongly depend on the in situ conditions of the reservoir, the lab and field data had to be adapted considering the temperature and pressure of the reservoir. Thus, the outcrop analogue data was compared with in situ data from deep hydrocarbon exploration wells to develop empiric algorithms for the depth and temperature dependence of the hydraulic properties. For the thermophysical properties established equations from crustal scale thermal models were used.

Evaluation of the deep geothermal potentials are based on the various rock and reservoir properties stored in the 3D geothermal model which were assessed using a Analytic Hierarchy Process (AHP) based multiple criteria decision support system to identify and visualize different geopotentials cell based incorporating their relevance for different deep geothermal systems. Depending on the chosen parameters, the model is highly capable to evaluate many different geopotentials. Therefore, threshold values based on technical constraints for each parameter were defined specifying whether the potential is very high, high, medium, low or very low.

The resulting geothermal model, which incorporates the quantification and the analysis of the deep geothermal potentials, is an important tool, which can be used at an early stage of the planning phase for the design of geothermal power plants. Furthermore, it allows quantification of the deep geothermal potential and is intended to be an instrument for public information.

1. INTRODUCTION

Germanys deep geothermal potentials for electric power production have been evaluated so far on large scale studies only (cf. Paschen et al., 2003). For the federal state of Hesse no potentials were denominated. Nevertheless, smaller regional studies focused on the Upper Rhine Graben based on the underground temperature and exploration data from the hydrocarbon industry only stated potential of selected reservoir horizons in the Hessian part of the northern Upper Rhine Graben (Hänel and Staroste 1988, 2002, Hurter and Schellschmitt 2003). As an outcome of the study of Paschen et al. (2003) the project "Geothermal Information System of Germany" (GeotIS) was initiated in 2005 with the aim to detect all hydrothermal potentials for electric power production in Germany (Schulz et al. 2009). However, the regions of interest of this project did not include the federal state of Hessen.

To bridge this gap the project "3D-modelling of the deep geothermal potentials of Hesse" was initiated in 2008 with the aim to systematically detect and evaluate all deep geothermal potential of Hesse and not only the comparably easy accessible hydrothermal potentials of the Upper Rhine Graben.

Comprehensive data sets for deep geothermal potential evaluation of Hessen so far only existed for the underground temperature in the region of the Upper Rhine Graben which is only a small part of the state area. In addition to the temperature the bulk permeability of the reservoir, respectively the achievable flow rate of thermal water is the main factor of influence on the deep geothermal potential for open systems. Additionally, matrix permeability, porosity and thermal conductivity are important factors to estimate the conductive and convective heat flows within the reservoir. For assessment of the deep geothermal potential, knowledge of geological structure and geothermal properties of potential reservoir rocks are indispensable. None of the above-mentioned parameters were available for the identified reservoir formations and therefore had to be collected state-wide in bibliographic, archive and most importantly in outcrop analogue and drill core investigations. The thus established vast database could then be connected with the 3D structural model and the underground temperature for parameterization with thermophysical and hydraulic properties.

The resulting geological-geothermal 3D-model (Sass and Hoppe, 2011) allows for a comprehensive evaluation of all deep geothermal potentials of Hesse and is capable to display the potentials for open systems like hydrothermal or petrothermal (EGS) systems as well as for closed systems like deep borehole heat exchangers (Bär et al., 2011).

2. GEOLOGICAL 3D MODEL

The 3D modelling was conducted using the GOCAD software and techniques (Mallet 2002). The model covers more than 21,000 km² (Fig. 1). It consists of the stratigraphic model units of Quaternary/Tertiary in a combined unit, the Muschelkalk, Buntsandstein, Zechstein, Permocarboniferous and the Pre-Permian, divided into “Mid-German Crystalline Rise”(MGCR) and “Rheno-Hercynian and Northern Phyllite Zone”(RH & NPZ) and is designed for deep geothermal potential evaluation.

The geological model of the Federal State of Hesse (Germany) (Arndt, 2012) is based on the geological survey map 1 : 300,000 (GÜK 300; HLUG 2007). Additional input data were well data, geological cross-sections, isopach, contour and paleogeographic maps as well as existing structural 3D models (Fig. 2).

More than 4,150 well data sets from the well database of the state geological surveys of Hesse (HLUG) and Lower Saxony (LBEG) were used. Besides well data 318 geological cross sections from geological maps and from other literature with a total length of more than 3,700 km have been implemented (Arndt et al., 2011). Furthermore, more than 1,500 2D seismic profiles from hydrocarbon or potassium salt exploration campaigns were assessed of which 29, which were published earlier within other research projects, were chosen for modelling.

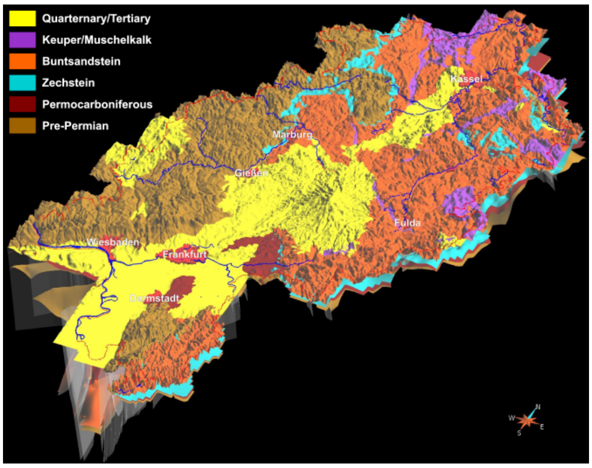


Figure 1: Overview of the geological 3D model of the federal state of Hessen showing the extent and the model units as well as major fault systems. The location of major cities and rivers are given for orientation.

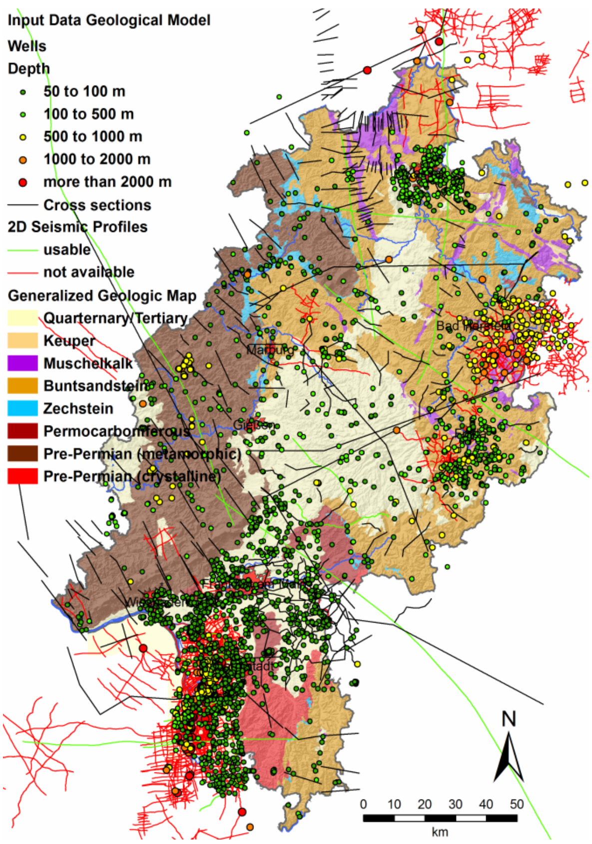


Figure 2: Simplified geological survey map of the location of input data for the geological 3D model including depth of the well data. Isopach our contour maps as well as existing 3D models which were incorporated into the model are not shown.

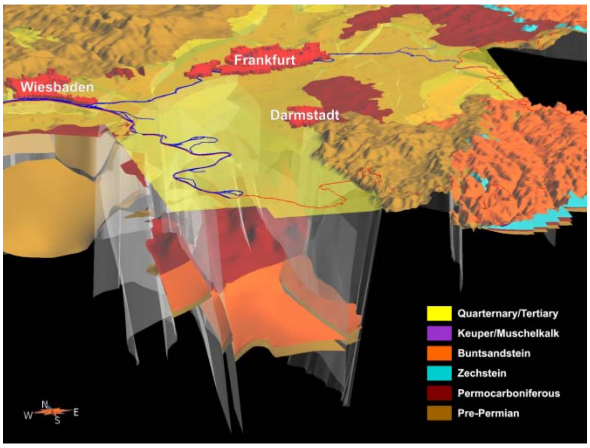


Figure 3: Detail of the geological 3D model showing the area of the northern Upper Rhine Graben with the potential hydrothermal reservoir units Buntsandstein and Permocarboniferous bounded by the graben faults. Five times vertically exaggerated.

Faults with a vertical displacement of at least 200 m were modelled. Unlike other geological 3D models at this scale these fault zones were not modelled as vertical planes but with their true dip angle as observed in the field or from seismic profiles (Fig. 3).

3. TEMPERATURE MODEL

For the assessment of deep geothermal potentials, the reservoir temperature is the key parameter. Therefore, the temperature distribution in the subsurface had to be modelled to a depth of 6 km below surface.

As the temperature data distribution is very poor for the entire Federal State of Hesse (Fig. 6), the subsurface temperature could not have been modelled with a pure interpolation approach (cf. Agemar 2009). A numerical approach as it is described in Cloetingh et al. (2010) and Förster and Förster (2000) was not feasible at the time of modelling due to the lack of sufficient data of radiogenic heat production rates and the at this time not yet finished geothermal 3D model. Numerical temperature modelling was performed with the data presented here subsequently by Rühaak et al. (2012).

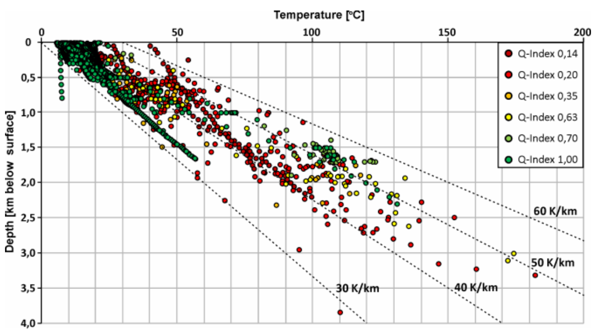


Figure 4: Temperature vs. depth plot of all available temperature data for Hesse. Q-Index as described in Table 1.

To create the first subsurface temperature model for the entire state of Hesse a combined interpolation supported by geologic a priori knowledge approach was chosen. Thus actual data measured in deep wells (Fig. 4) was combined with the annual mean surface temperatures and regionally varying geothermal gradients derived from borehole temperature measurements in connection with the Mohorovičić Discontinuity depth map from Dèzes and Ziegler (2001) to support subsurface temperature modelling as described by Arndt et al. (2011).

Input data were 2,029 point datasets provided by the Geophysics Information System (FIS GP) of the Leibniz Institute for Applied Geophysics (LIAG) and the geophysics archive of the HLUG. Their depths range from 150 to 3,061 m below ground surface in Hesse. Data with depths of less than 150 m have not been used, due to their low relevance for deep geothermal applications and to avoid artefacts due to shallow measurements near thermal springs, seasonal influences or palaeoclimatic signals.

Table 1: The different quality indices of the temperature measurements (modified after Rühaak et al. 2012)

Quality Index	Type of Measurement	Est. Error [K]	No.
1.00	Undisturbed Temperature Logs	0.01	1,360
0.70	Bottom Hole Temperature (BHT) with at least 3 temperature measurements taken at different times in the same depth; corrected with a cylinder-source approach	0.5	58
	Drill Stem Tests (DST)		
0.63	BHT with at least 3 temperature measurements in the same depth; corr. with the Horner-Plot Method	0.7	85
	BHT with at least 2 temperature measurements taken at different times in the same depth; corr. with a explosion line-source approach		
0.35	BHT with one temperature measurement, known radius and time since circulation (TSC)	1.6	46
	BHT with one temperature measurement, known TSC		
0.20	Disturbed Temperature Logs	2.4	200
0.14	BHT with one temperature measurement, known radius	3.0	280
	BHT with one temperature measurement, unknown radius and unknown TSC		

For the interpolation variogram analysis was conducted using high quality data from undisturbed temperature logs (Table 1) which were trend adjusted with a geothermal gradient of 3 K/100 m and an annual mean surface temperature of 10 °C (Arndt et al., 2011 and Rühaak et al., 2012).

The resulting subsurface temperature model fits the temperature measurements, which reach a maximum depth of 3,105 m inside and 1,658 m outside the Upper Rhine Graben within a range of about ±10 K. Inaccuracies in areas where temperature data are missing or where temperature data were measured in hydrothermal convection zones might still occur. However, this model allows an improved prognosis of the temperature in the subsurface with an accuracy of ±5 K ± 5 K/km depth and can be used to create temperature maps for various depths as well as maps of the depth of various isotherms (Fig. 5).

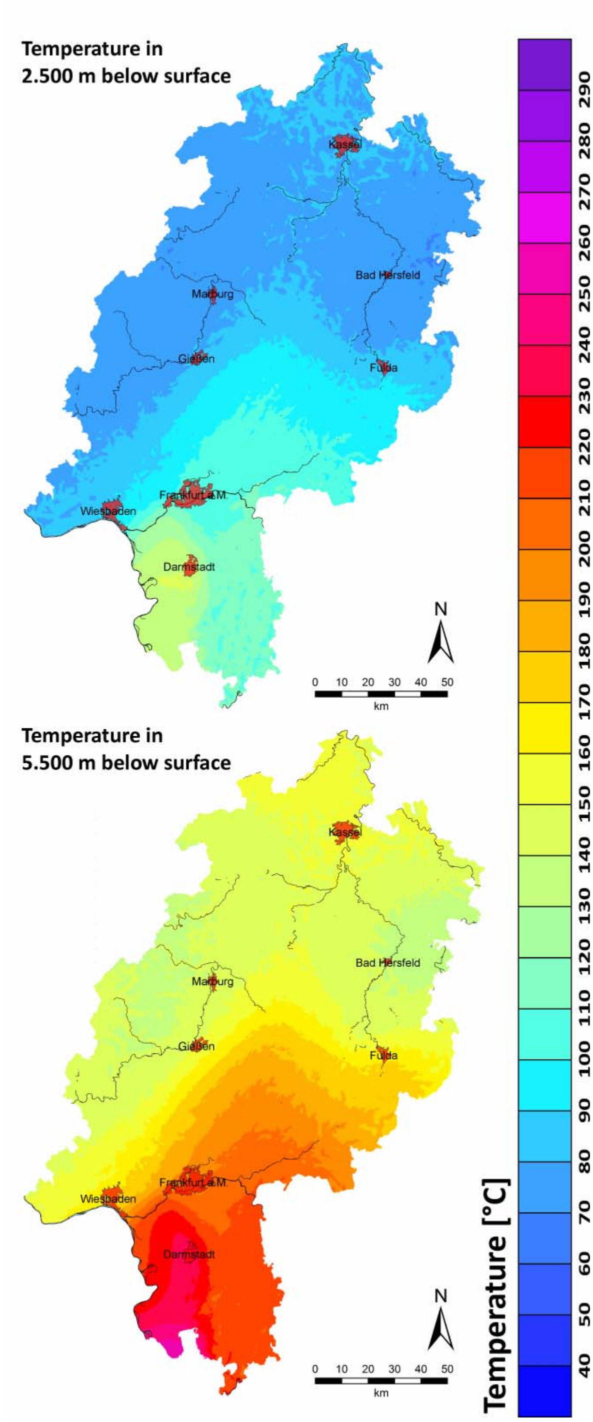


Figure 5: Maps of the Temperature in 2,500 and 5,500 m below surface respectively as an exemplary output of the temperature model.

4. GEOTHERMAL 3D MODEL

Permeability and thermal conductivity are key parameters in geothermal reservoir characterization (Tester et al., 2006). In previous publications and databases, the number of investigations where more than one key parameter was measured on the same sample is very low. According to the thermo-facies concept by Sass and Götz (2012) geothermal parameters should be determined in one coherent approach on the same set of samples for each facies type.

4.1 Input Data

To allow predictions of the geothermal properties, a data set of outcrop analogue studies of more than 600 locations, borehole data of more than 25 boreholes and core investigations of more than 500 m of cores as well as hydraulic test data of more than 900 boreholes has been compiled for all relevant formations (Fig. 6).

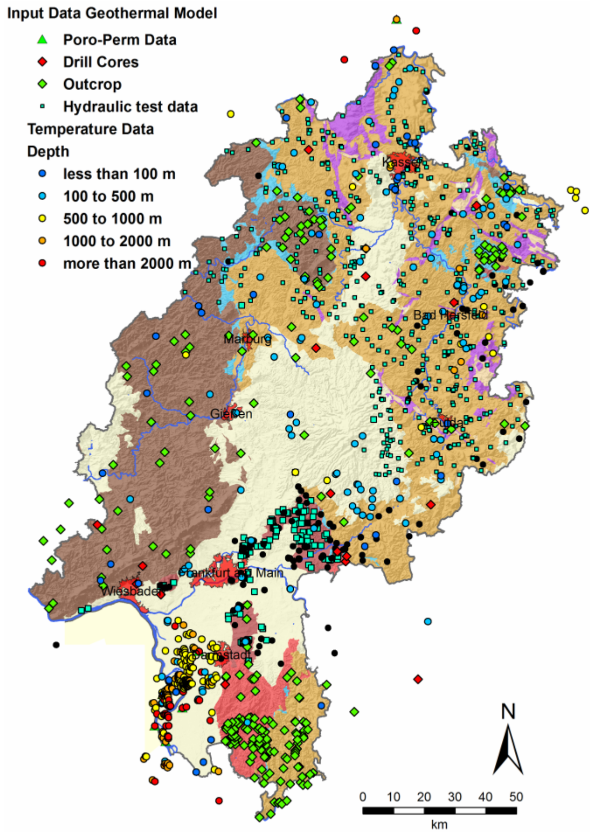


Figure 6: Simplified geological survey map of the input data used for the geothermal 3D model showing the locations of all outcrop analogue study locations conducted and all drill cores, temperature data points, Poro-Perm data sets, and hydraulic test data sets available.

Systematic measurements of thermophysical and hydraulic rock properties such as thermal conductivity, thermal diffusivity, heat capacity, density, porosity and permeability were conducted on oven dry samples for each sample respectively (Bär et al., 2011). Thus a vast geothermal database comprised of more than 25.000 measurement altogether has been created. Due to the large number of measurements the database is ideal for statistical analysis of each parameter (Table 2) and correlation analysis between the different parameters. The results of the statistical analysis allow to stochastically analyze the probability of occurrence as well as for exploration risk analysis.

Table 2: Excerpt of the geothermal data base for the model units showing the arithmetic mean ± standard deviation and number of measurements (n) for thermal conductivity, specific heat capacity and matrix permeability.

Model Units		Thermal Conductivity [W/(m·K)]	n	Specific Heat Capacity [J/(kg·K)]	n	Matrix Permeability [log m²]	n
Tertiary Basalts		1.81 ± 0.26	329	683 ± 90	419	-16.0 ± 1.0	364
Muschelkalk		2.01 ± 0.39	316	675 ± 88	125	-16.1 ± 0.8	309
Buntsandstein		2.57 ± 0.47	2,140	705 ± 90	1,029	-13.6 ± 1.1	2,685
Zechstein		2.26 ± 1.15	970	796 ± 278	763	-15.1 ± 1.2	958
Permocarbon		2.21 ± 0.67	1,438	758 ± 160	590	-14.1 ± 1.4	882
Pre-Permian	RH & NPZ	2.71 ± 1.12	2,105	648 ± 150	1,512	-15.8 ± 1.0	1,386
	MGCR	2.40 ± 0.38	1,176	755 ± 75	966	-16.4 ± 0.9	926
GESAMT			8,474		5,404		7,599

Thermal conductivity and thermal diffusivity were measured using an optical thermo scanning device (Lippmann & Rauen) after Popov et al (1999). Density and porosity were investigated using the helium pycnometer AccuPyc 1330 (micromeritics) and the powder pycnometer GeoPyc 1360 (micromeritics) to measure both the grain density and bulk density of each sample and thus be able to calculate porosity. Matrix permeability was measured with an combined probe- and column-gas-permeameter (Hornung and Aigner, 2002) able to measure both apparent and intrinsic permeability sensu Klinkenberg (1941).

Heat capacity is calculated with the Debye-Equation:

$$\rho_r = \frac{\lambda}{c_r \cdot \alpha} \qquad [1]$$

where ρ_r is the density [kg/m³]; c_r, specific heat capacity [J/(kg·K)]; λ, thermal conductivity [W/(m·K)]; α, thermal diffusivity [m²/s].

The error of the optical scanning as well as density and porosity measurements does not exceed 3 %. The error of the permeability measurements is dependent on the order of magnitude of the permeability (Bär et al., 2011). The total error increases from 5 % above $K = 1 \cdot 10^{-13}$ m² to about 400 % at $K = 1 \cdot 10^{-18}$ m². Considering the purpose of this approach and alternative measurement methods in low permeable rock, an order of magnitude is a satisfactory accuracy.

All measurements were conducted on oven-dried samples to achieve the required reproducibility of results. Thus, depending on the lithology, the measurement error is significant reduced. To transfer these data to reservoir conditions many correction approaches for saturated conditions were discussed e.g. by Hartmann et al. (2005, and references therein). Within the project the theoretical approach of Lichtenecker was chosen:

$$\lambda_r = \lambda_{fluid}^{\Phi} \cdot \lambda_{matrix}^{n-\Phi} \qquad [2]$$

where λ_r is the thermal conductivity of the reservoir [W/(m·K)], λ_{fluid} of the fluid [W/(m·K)], λ_{matrix} of the matrix [W/(m·K)] and Φ the porosity [-].

4.2 Model Parameterization Parameterization of a geological 3D model requires volumetric 3D objects and not only the 2D surfaces of geological horizons and faults. Therefore, the GOCAD object stratigraphic Grid (s-grid) for which an infinite amount of cell based properties (e.g specific heat capacity) can be defined. Furthermore, the s-grid can be fitted to the geological horizons and can be cut by fault surfaces exactly and has no constraints on the size of its cells (Mallet, 2002). How to build s-grids is described in general by Mallet (2002) and in the special case of this project in detail by Arndt (2012).

Since both the hydraulic and thermophysical properties strongly depend on the *in situ* conditions of the reservoir, the values for saturated conditions derived from the lab and field data need to be adapted considering the temperature and pressure within the reservoir. Therefore, the outcrop analogue data was compared with in situ data from deep hydrocarbon exploration wells to develop empiric functions for the depth and temperature dependence of the hydraulic properties (Bär 2012), which are consistent with comparable dependencies derived by other studies (Welte et al., 1997; Ingebritsen & Manning 1999; Manning and Ingebritsen, 1999; Stober and Bucher, 2007). For the thermophysical properties established functions from crustal scale thermal models were used for the adaptation to reservoir conditions (Zoth and Haenel, 1988; Somerton, 1992; Pribnow, 1994; Vosteen and Schellschmidt, 2003; Adulagatova et al., 2009) .

Using these equations and the temperature model the different s-grids of the model units were parameterized directly in GOCAD with the depth and temperature corrected properties of the different units respectively: thermal conductivity, thermal diffusivity, density, specific heat capacity, porosity, matrix permeability and bulk rock permeability. Additionally, bulk rock permeability was gradually increased in the vicinity of fault systems towards the fault by two orders of magnitude to account for the positive effect of the fault damage zones on the hydraulic properties (Caine et al. 1996, Evans et al. 1997, Faulkner et al. 2010). Finally transmissibility was calculated based on the fault corrected bulk rock permeability and the vertical thickness of the model units.

4.3 Quantification of the geothermal potential

First steps of reservoir potential evaluation include the quantification of the heat in place following the volumetric approach of Muffler and Cataldi (1978). Heat in place is calculated directly for each model unit in the geothermal model which is hotter than 60 °C using Eq. 3 and is therefore quantified regionally and geologically in great detail. The Federal German Geothermal Potential Study (Jung et al., 2002) also applied this approach. On the other hand, Bundschuh and Suarez Arriaga (2010) introduced different more complex approaches.

$$E_{th} = c_r \cdot \rho_r \cdot V \cdot (T_r - T_s) \quad [3]$$

Where E_{th} is heat in place [J], c_r the specific heat capacity [J/(kg·K)], ρ_r the density [kg/m³], V the reservoir volume [m³], T_r the reservoir temperature [°C] and T_s the surface temperature [°C] respectively. Reservoir porosity and heat stored in the reservoir fluids are neglected due to errors of less than 5 % for regional scale studies (Muffler and Cataldi, 1978) if porosity is lower than 20% which is the case for all deep geothermal reservoir formations in Germany. Consequently it is unlikely to overestimate the potential with this conservative approach.

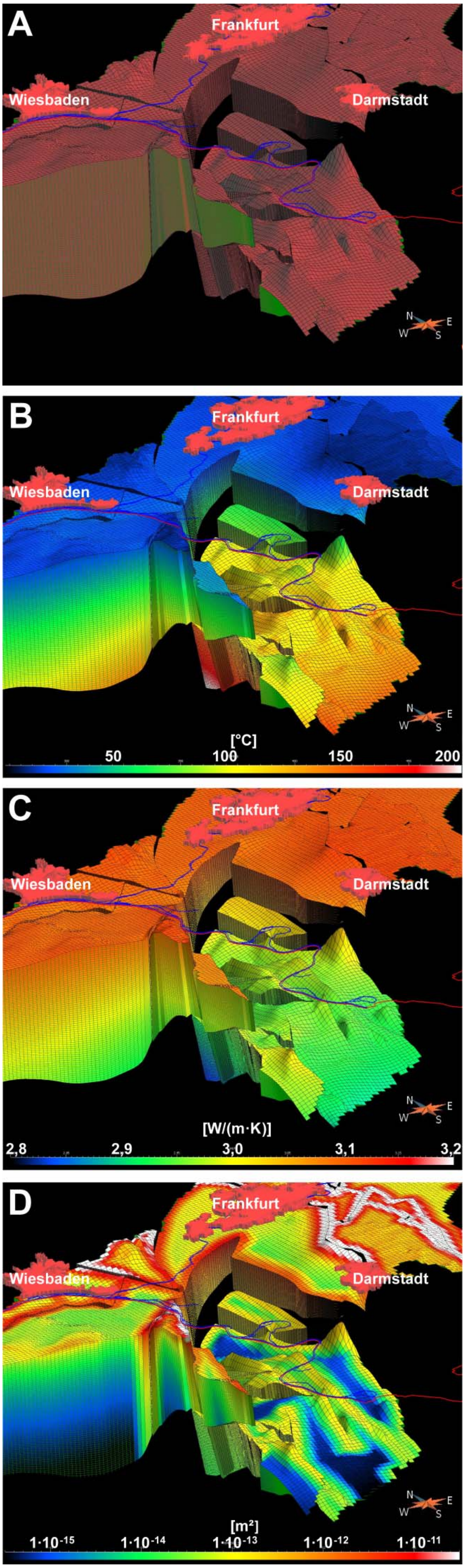
The next step is to assess the extractability of heat and the power production potential considering known heat extraction rates and technical degrees of efficiency. These factors differ according to temperature, effective porosity and depth of the reservoir as well as to the project layout and should strictly speaking be evaluated for each location separately. Nonetheless, generalized values can be defined following framework requirements based on benchmark parameters proposed by Jung et al. (2002, Table 3).

Table 3: Benchmark parameters to define the technical degrees of efficiency for power production with binary power plants (mod. after Jung et al., 2002), PHC = Power-Heat Cogeneration, HP = Heat Pump.

Parameter	Value
Minimum Reservoir Temperature T_{MIN}	100 °C
Maximum Drilling Depth Z_{MAX}	7 km
Minimum Extraction Temperature T_{MIN}	100 °C
Injection Temperature of Thermal Water (pure power production) T_{IN}	70 °C
Injection Temperature of Thermal Water (PHC without HP) T_{IN}	50 °C
Injection Temperature of Thermal Water (PHC with HP) T_{IN}	30 °C

Based on these parameters the potential for geothermal power production was calculated only for reservoir volumes which temperature exceeds 100 °C, while parts with temperatures between 60 °C and 100 °C are only suited for direct heating.

Figure 7: S-grid of the Permocarboniferous (A) parameterized depth and temperature corrected with temperature (B), thermal conductivity (C) and bulk permeability (D), including the influence of fault systems on the hydraulic properties.



4.4 Geothermal potential evaluation

To analyze the deep geothermal potentials the various rock and reservoir properties were assessed using a multiple criteria approach incorporating their relevance for the different geothermal systems. For a hydrothermal system for example bulk rock permeability, respectively transmissibility and temperature are by far the most important parameters and will therefore have a much stronger impact on the potential than e.g. thermal conductivity. The geothermal model of Hessen was used to evaluate the deep geothermal potential of hydrothermal, petrothermal and closed geothermal systems simultaneously. For detailed descriptions on the background of this newly developed method for geopotential evaluation with GOCAD, which is based on the very common multi criteria decision support system of the Analytic Hierarchy Process (AHP) introduced by Saaty (1980, 1990, 2005) see Arndt et al. (2011) and Arndt (2012).

Table 4: Threshold values for the definition of the geothermal potential classes

Potential	very low	low	medium	high	very high
Thermal Conductivity [W/(m·K)]	< 1.25	> 1.25	> 2.0	> 3.0	> 5.0
Thermal Diffusivity [10^{-6} m²/s]	< 0.6	> 0.6	> 1.0	> 1.5	> 2.0
Reservoir Temperature [°C]	< 60	> 60	> 100	> 120	> 150
Permeability [m²]	$<5\cdot10^{-15}$	$>5\cdot10^{-15}$	$>1\cdot10^{-13}$	$>5\cdot10^{-13}$	$>4\cdot10^{-12}$
Transmissibility [m³]	$<5\cdot10^{-13}$	$>5\cdot10^{-13}$	$>5\cdot10^{-12}$	$>3\cdot10^{-11}$	$>1\cdot10^{-10}$
normalized potential for multi criteria analysis	0.0 - 0.2	0.2 - 0.4	0.4 - 0.6	0.6 - 0.8	0.8 - 1.0

The method is highly capable to identify and visualize different geopotentials cell based using many different parameters determining each potential. Therefore, threshold values, based on geothermal technical framework requirements for each parameter were defined specifying whether the potential is very high, high, medium, low or very low (Table 4, cf. Bär, 2012). High to very high deep geothermal potentials were defined so that the natural reservoir conditions are more than sufficient for economically feasible electric power production, medium potential so that it is feasible considering federal R&D grants, low to very low potential that it is only usable for district heating or if measures to enhance reservoir properties are applied.

5. RESULTS

Medium to high hydrothermal potentials with more than 600 TWh of power production potential have been identified for the Permocarboniferous and the Buntsandstein successions within the northern Upper Rhine Graben and the adjacent Saar-Nahe Basin in the west (Fig. 8).

Depending on the depth, reservoir temperature and transmissibility high hydrothermal potentials of the Permocarboniferous are located along major faults within the Graben where higher bulk rock permeabilities are expected. Medium potentials were identified for the Permocarboniferous for almost the entire graben region in depths of more than 2,000 m (Fig. 8 and 9).

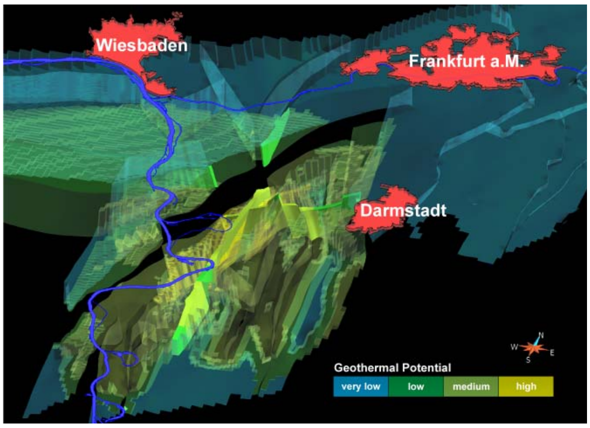


Figure 8: Detail of the geothermal 3D model showing the hydrothermal potential classes of the Permocarboniferous in the northern Upper Rhine Graben. Major cities and rivers at the ground surface are given for orientation. Five times vertically exaggerated.

Similar results were obtained for the Buntsandstein succession which is located further to the south and in the whole middle and southern Upper Rhine Graben but also plays a non negligible role in the Hessian part.

This local distribution of the potential classes shows that the results of the hydrothermal potential evaluation strongly depend on the transmissibility or bulk rock permeability being increased along fault zones. In combination with the sensitivity towards temperature it illustrates that the newly developed method is well suited to identify areas where successful hydrothermal exploitations are most promising.

High petrothermal potentials with more than 10,000 TWh of power production potential were identified for the granites, granodiorites and gneises (felsic intrusive and metamorphic rocks) of the MGCR below the northern Upper Rhine Graben where temperature exceeds 150 °C in depths of more than 3 km. Due to the strong tectonic segmentation of the Upper Rhine Graben and its associated damage zones even higher bulk rock permeabilities than used for the parameterization of the model can be expected in the basement rocks. In comparison, mainly medium petrothermal potentials were identified for the crystalline or metamorphic bedrocks in other regions of Hesse.

With exception of the quartzites, sandstones and greywackes of the Taunus mountains, where about 5,000 TWh of power production potential are to be expected, the low metamorphic rocks of the RH and NPZ are due to an abundance of metapelitic rocks not well suitable for petrothermal exploitation or reservoir enhancement by hydraulic fracturing. Just as much as the intrusive rocks of the MGCR, the quartzites, sandstones and greywackes show high to very high thermal conductivities and promising mechanical properties and have therefore been identified as high petrothermal potential reservoirs. If these units occur in suitable depths with high temperatures and close to major fault or fracture zones exploitation and stimulation measures to enhance permeability become feasible.

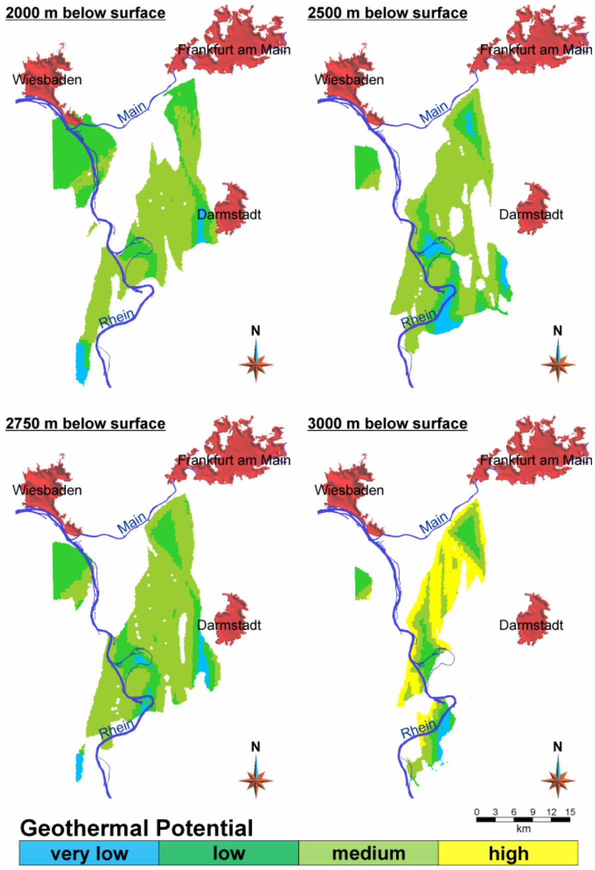


Figure 9: Map of the hydrothermal potential classes of the Permocarboniferous in the northern Upper Rhine Graben in depths of 2,000 m, 2,500 m, 2,750 m and 3,000 m below surface respectively.

Based on the current state of knowledge about the basement rocks of Hesse developed within the geological-geothermal 3D model the MGCR with its intrusive rocks is most likely better suited for petrothermal exploitation than the RH and NPZ with its metamorphic, mostly pelitic rocks. The most promising region for hydrothermal and petrothermal systems in Hesse remains the Upper Rhine Graben with its geothermal anomaly and its high fracture densitiy. Nonetheless, medium to high petrothermal potentials are also to be expected for the basement of the Odenwald, the Hanau-Seligenstädter-Basin and of the Wetterau up to the Rhön mountains, where no geothermal anomalies are known but petrophysical properties are well suited for EGS or petrothermal systems.

Table 5: Deep geothermal potential of the different Hessian hydrothermal and petrothermal (EGS) reservoir formations. *considering technical degrees of efficiency for binary geothermal power plants (see Table 3).

Reservoir Unit	Volume [km³]	Heat in Place [EJ]	Recover-able Heat [EJ]	Power Production Potential* [EJ]	Power Production Potential* [TWh]
RH+NPZ	43,394	12,220	463.5	55,2	15,345
MGCR	28,971	12,080	538.5	68,2	18,955
Buntsandstein	40.7	13.1	2,65	0,32	88
Permocarbon	442	102.8	17.01	1,92	531

In 2011 the mean annual electric power consumption of Germany was 540 TWh (BMWi, 2011). In comparison with the results of the deep geothermal potential quantification of the federal state of Hesse (Table 5), it is obvious that deep geothermal energy can play an import role in covering a vital part of the future energy demand by renewable energy sources. The hydrothermal potentials located within the Buntsandstein and Permocarboniferous reservoirs, which comprise 1.2 % of Hesse's overall geothermal potential, can already be exploited with state of the art binary power plants. The petrothermal potentials comprise about 98.2 % of the overall potential and can be exploited in the near future with EGS technology. This distribution of the potentials makes it obvious that future research activities should be focused on further exploration and exploitation techniques for petrothermal systems.

6. CONCLUSIONS

The resulting geothermal model, which incorporates the quantification and the analysis of the deep geothermal potentials, is an important tool, which can be used at an early stage of the planning phase for the design of geothermal power plants. Furthermore, it allows quantification of the deep geothermal potential and is intended to be an instrument for public information.

It is the first geological-geothermal 3D model of a whole federal state of Germany which allows for the evaluation of deep geothermal potentials. The vast geothermal data base permits a reservoir prognosis on statistically confirmed parameters. Additionally, all thermophysical and hydraulic parameters are depth and temperature corrected so that over- or underestimations of the reservoir potentials are highly unlikely. Therefore, the highly flexible multi criteria approach used for potential evaluation, which can also be applied to all kinds of other geopotentials, yields highly reproducible results allowing a potential classification for the whole federal state which in combination with the quantification of the usable heat stored underground allows for the identification of economically feasible locations for geothermal power plants. Furthermore, due to the statistically confirmed parameterization of the model it is capable of exploration risk prognosis and can also be used as a foundation for numerical reservoir models.

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