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Probability of success studies for geothermal projects in clastic reservoirs: From subsurface data to geological risk analysis

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ABSTRACT

In the realisation of a geothermal project, an important step is the quantification of the geological risk of a well not achieving the economically necessary cut-off values with respect to temperature and flowrate/drawdown. In this paper, we present a new method for calculating this risk via a probability of success study by using all available types of hydraulic data, including porosity values derived from core samples or borehole logs. This method has been developed for geothermal projects in fluvial sandstones of the North German Basin but can be applied to any clastic, not fracture-dominated reservoir worldwide.

1. Introduction

Geothermal energy provides base-load capable renewable energy not only for electricity but also for district heating. In many countries such as Italy, New Zealand and USA, the advantages geothermal energy offers have been exploited for many years with regard to the electricity production (e.g. Aneke and Menkiti, 2016). However, geothermal installations for district heating systems provide the opportunity to tap the Earth's vast energy supply even in areas less favourable for geothermal electricity production due to disadvantageous thermal and/or hydraulic properties of the subsurface.

In the North German Basin (NGB), district heating systems such as Waren and Neustadt-Glewe already exist, which were constructed during the times of the former German Democratic Republic, resulting in a production history of about 30 years (Seibt and Kellner, 2003). Both sites are targeting an aquifer of Raethian age (Upper Keuper), which is one of the preferred reservoirs for geothermal exploration in the NGB, where several aquifers with high permeabilities are situated in depths of 1–2.5 km with resulting temperatures below 100 °C (Hurter and Hänel, 2002). Even though several geothermal projects have been developed in the past 30 years, they have mainly been small scale and often for balneological purposes. Larger geothermal district heating systems are possibly lacking due to the heterogeneity of hydraulic reservoir characteristics. Even though more than 18,000 wells were drilled onshore in the NGB by the hydrocarbon industry (State Authority for Mining, Energy and Geology, 2017), hydraulic data of aquifers relevant for geothermal production are sparse. Reservoir heterogeneity and sparse data pose a challenge for probability of success (POS) studies which are used to assess the geological risk of a potential geothermal project (Schulz et al., 2005, 2007; van Wees et al., 2012; Ganz, 2015; Bär and Sass, 2015). Other types of POS studies for geothermal projects which focus on the later stages of geothermal project development such as assessing borehole-related risks (Melosh, 2017) or the thermal capacity of the geothermal facility (Stober et al., 2013) are not within the scope of this paper.

POS studies are often required to procure an insurance for a planned geothermal project. Developers of such projects are in many cases municipalities or private investors who cannot afford for the project to fail. Therefore, they try to cover the financial loss of an unproductive well by procuring an insurance against this worst-case scenario. In this context, an unproductive well describes a well not reaching the energy output necessary for an economically successful project. POS studies quantify not only the geological risk of the planned project but also the risk the insurance company faces if it gets involved. Thus, the results of a POS study may not only determine whether a project will be insured at all but may also be used as a basis to negotiate the insurance premium in case of favourable results. Hence, the existence and outcome of a POS study is often crucial for geothermal project development and the inability to provide such a study due to a lack of data may lead to early project termination.

The sparsity of subsurface data used to prepare a conventional POS study (as detailed in e.g. Schulz et al., 2007; Ganz, 2015) therefore poses a significant hindrance to the development of geothermal projects in the NGB. Even though the number of wells drilled in this area is

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large, the available data for a POS study, i.e. temperature and hydraulic data, are limited. To overcome this lack of data, a new method has been developed which utilises different types of data and offers a chance to assess the geological risk even in areas with a so far sparse database. Even though this method has been developed for use in the NGB, it can easily be extended to other areas worldwide.

The reservoir property most difficult to assess is permeability. Hydraulic well tests from potential geothermal reservoirs are sparse as most existing data stems from hydrocarbon wells, which were seldom tested for non-hydrocarbon-bearing strata. However, in the NGB several thousand core measurements of effective porosity and permeability were taken in geothermally relevant layers so that a correlation function between these two parameters could be established. Various models to establish such a mathematical correlation have been developed for sedimentary rocks including sandstones (Nelson, 1994). Pape et al. (1999) describe several correlation equations based on a fractal model of pore spaces within sandstones, which have been adapted to different rock types – from sandstones to shales – mainly found in the NGB. A similar approach to utilise existing porosity data in order to calculate permeability has been published for Denmark (Mathiesen et al., 2011; Kristensen et al., 2016). Here, the Kozeny equation (Kozeny, 1927) has been adapted to meet the data from Danish fluvial sandstones equivalent to the Rhaetian sandstones in the NGB.

In this paper, we present a new method based on a synthetic example of a geothermal project within the North German Basin. The heterogeneous structure of potential geothermal reservoirs in this area allows for the specification of all steps required for a complete POS study.

2. Geology

The North German Basin is an area for geothermal exploration in Germany. The NGB is part of the Central European Basin system with a sedimentation history from the Late Carboniferous to the Cenozoic, resulting in a sediment column of up to 10 km. Several Mesozoic reservoirs are widely present in the NGB and form potential aquifers suitable for geothermal exploitation especially for heating purposes (e.g. Feldrappe et al., 2008; Wolfgramm et al., 2008). In this study, we focus on Rhaetian sandstones (Upper Keuper), which locally exhibit temperatures and effective permeabilities high enough for an economically successful geothermal project.

In late Triassic times, the Central European Basin stretched from Scandinavia to Northern Switzerland and from England to East Poland (Stampfli and Borel, 2001). Marine conditions during the Mid Triassic time (Muschelkalk Sea) were subsequently replaced by terrestrially dominated environments of the Upper Triassic Keuper succession. Sediments of the Keuper in the NGB were deposited in various environmental settings ranging from marine, deltaic and lagoonal to fluvial (Bachmann et al., 2010). Prominent sandstone intervals are recorded in the Middle Keuper subgroup (Stuttgart formation, 'Schilfsandstein') and in the Upper Keuper (Exter formation or 'Rhaetian'). Both sandstone complexes were deposited in a general North–South trending network of fluvial channels and a fluvial-plain to fluviodeltaic environment (Beutler and Nitsch, 2005). In the study area, the Middle Keuper ('Schilfsandstein') consists of claystone and sandstone deposited with maximum sandstone thicknesses in a range from 5 m to 60 m (Feldrappe et al., 2008). The aquifer properties of the 'Schilfsandstein' are in general moderate. Despite high effective porosities of up to 35% of sandstones deposited in fluvial channels, effective permeabilities measured at cores show relatively low values of 15–130 mD (Wolfgramm et al., 2008). However, Franz et al. (2018a) report higher values for the mean effective permeability of the 'Schilfsandstein' with 443 mD for the lower unit and 546 mD for the upper unit indicating its geothermal potential in specific locations.

The sandstone units of the Upper Keuper (Rhaetian, Exter formation) were deposited in a similar environment as the underlying 'Schilfsandstein'. The Rhaetian delta complex is widely present in the northeastern part of the NGB and consists of an alternation of claystones, siltstones and greyish sandstones. Several prominent sandstone units like the so-called 'Postera sandstone', the slightly younger 'Contorta sandstone' and locally the 'Triletes sandstone' are present in the Exter formation (Feldrappe et al., 2008). In general, sandstones were deposited in fluvial and deltaic distributary channels (Franz and Wolfgramm, 2008). In the central part of the NGB, the sand-dominated lower delta plain intersperses with fine-grained deposits of the delta front and prodelta sediments (Batermann, 1989; Gaupp, 1991; Bachmann et al., 2010). The fluvial-dominated sandstone units are characterised by a relatively low clay content, high effective porosities between 20% and 35% and effective permeabilities measured at cores of more than 500 mD (Wolfgramm et al., 2008). The fairly good reservoir properties of the fluvial channel deposits with average thicknesses of 10–30 m and partly even up to 60 m make this aquifer complex a significant potential geothermal reservoir in the NGB (Franz et al., 2015, 2018a).

3. Data coverage

Most of wells in the NGB date back to the 1950s and 1960s and have been abandoned since then. In general, oil and gas companies have not tested the aquifers thoroughly which are now the centre of attention for geothermal development. As a result, data coverage on the hydraulic properties of these strata is poor. For the whole NGB, there are about 300 reported hydraulic tests at about 100 locations. Given that locally there can be up to six aquifers potentially relevant for geothermal exploitation, the number of tests is much too small to be used for reservoir characterisation and evaluation of hydraulic properties.

3.1. Temperatures

Even though temperature data are available for thousands of wells within the NGB, in most cases the measurements consist of bottom-hole temperatures (BHT), which were usually taken shortly after drilling and are thus disturbed due to cooling during drilling operations. The available BHTs have been corrected to account for this but may still underestimate real aquifer temperatures (Förster, 2001).

Additionally, the depth of a potential geothermal aquifer in the NGB can vary by a few hundred meters to more than a thousand meters within short distances due to intensive salt tectonics. This naturally leads to significant temperature variations within a given aquifer, not only because of different depths but also as salt structures and their associated higher thermal conductivity (Norden and Förster, 2006) disturb the local thermal field significantly (e.g. Jensen, 1990; Norden et al., 2012). The distribution of salt intrusions and the locations of wells with temperature data are shown in Fig. 1.

3.2. Hydraulic data

For numerous wells, effective porosity data and sometimes also effective permeability data from core analysis of the geothermally relevant strata can be retrieved from a database maintained by the State Authority for Mining, Energy and Geology of Lower Saxony (LBEG). Examples of the available data are given by Kuder et al. (2014). Moreover, borehole logs for these strata, from which hydraulic properties can be inferred, are available for several dozen wells. The data mostly consist of sonic logs, but some neutron or litho-density logs are also available. The available hydraulic data for the case study in the Rhaetian sandstones are shown in Fig. 2. If there is more than one type of measurements per well, only the highest quality data class is depicted, with the order of decreasing quality being hydraulic tests, core measurements and lastly log data.

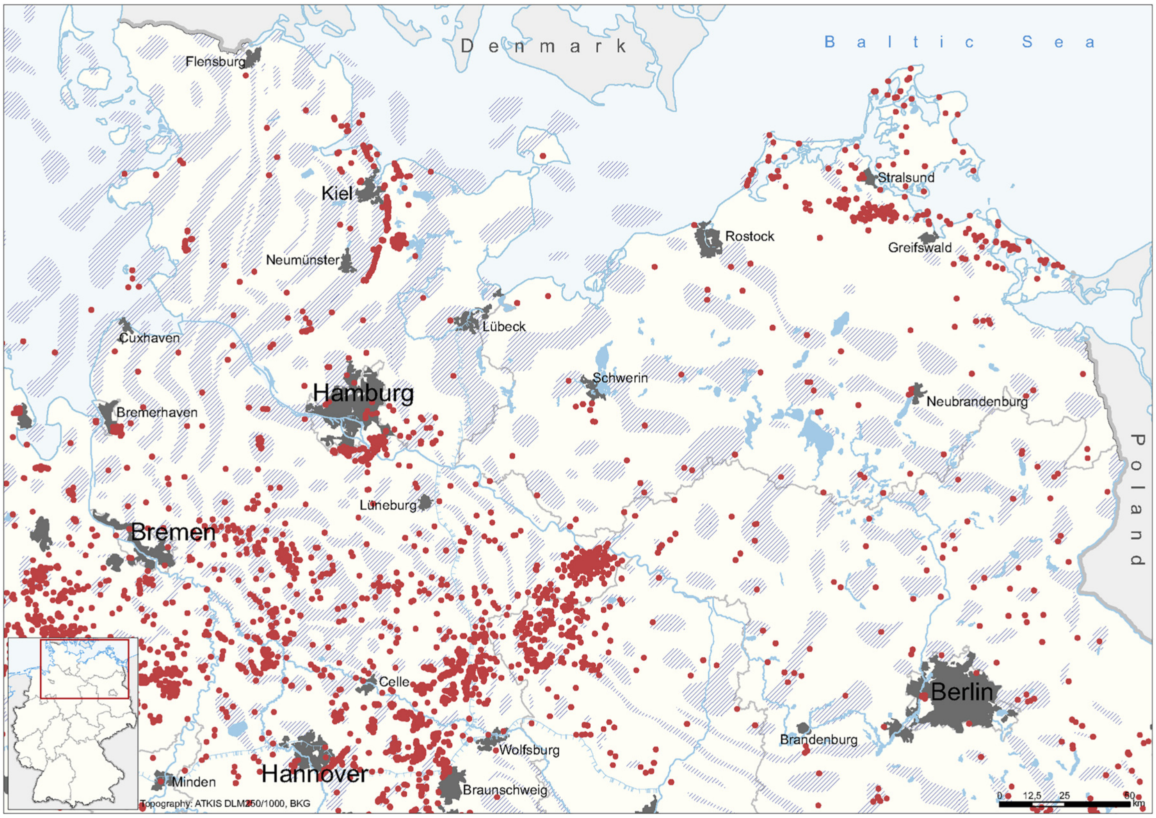

Fig. 1. Topographic map of northern Germany and adjacent areas. Red dots: wells with available temperature data. Dashed areas: salt structures (Reinhold et al., 2008).

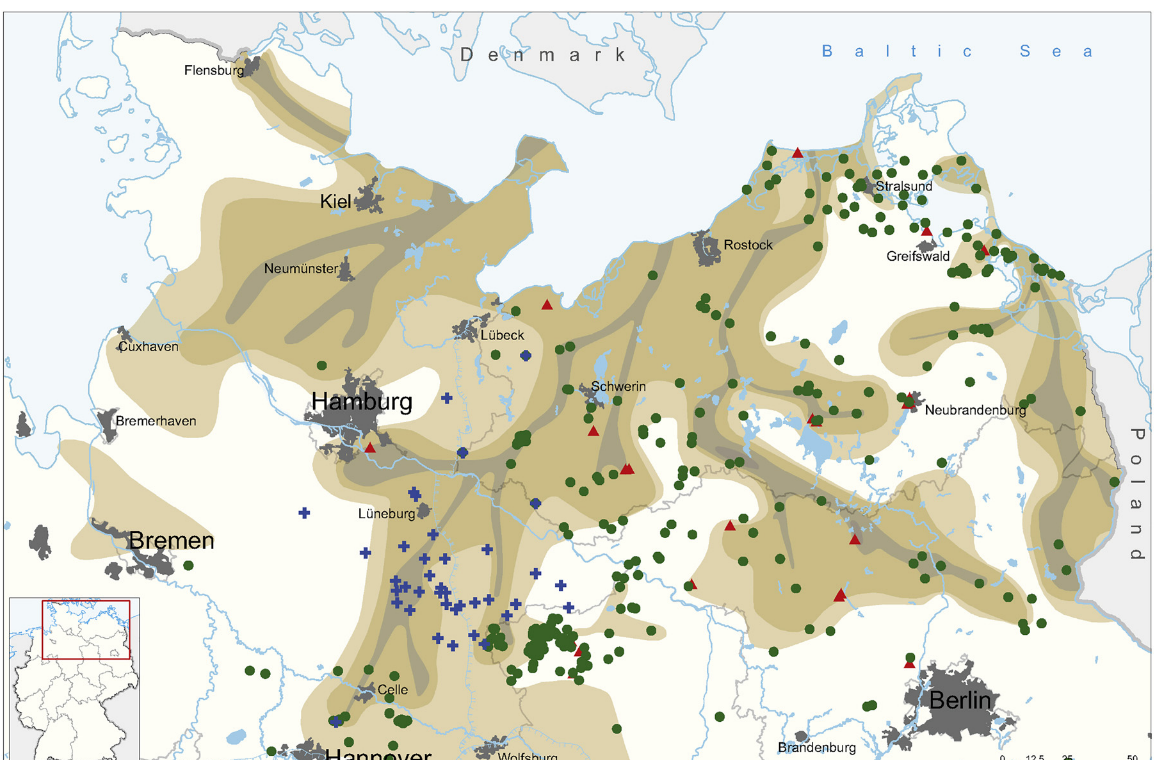

Fig. 2. Reconstruction of the depositional environments and sandstone thickness of the Rhaetian sandstones. The map is based on selected wells' data (after Franz et al., 2015) and hydraulic data available for the Rhaetian sandstones of the North German Basin. It shows the schematic distribution and sandstone thickness of fluvial and deltaic distribution channels (light brown: 0–10 m thickness, medium brown: 10–20 m thickness, grey: 20–50 m thickness, dark grey 50–100 m thickness). Red triangels: wells with hydraulic pump tests, green dots: wells with core measurements, blue crosses: wells with log data.

4. Method

4.1. POS calculation

The aim of the study is to analyse wells surrounding a planned geothermal project and compare their thermal and hydraulic properties to those required for economically successful operation in order to determine the geological POS for the project. The POS for the hydraulic and thermal properties is calculated via a statistical approach:

$$\mathrm{POS} = \sum_{i}^{n} \frac{x_i G_i \frac{1}{r_i}}{G_i \frac{1}{r_i}} \tag{1}$$

with n being the number of analysed wells [–], x_i the value of success [–], which can either be 1 if the well meets specified criteria of success or 0 if it does not, G_i the potential weighting coefficients [–] and r_i the distance of the analysed well to the planned project site [m]. Clearly, in order to achieve a reliable assessment of the situation as many wells as possible should be included into the analyses. Moreover, each well enters this equation only as a binary value via x_i. Weighting factors are optional and can e.g. be used to differentiate among different data sources or among wells in different geological settings. For this purpose, additional weighting factors can be introduced into Eq. (1).

For hydraulic properties, the criteria for success are defined via the main hydraulic parameters relevant for the economic success of a geothermal project, i.e. flow rate and the associated drawdown expected for the planned well. Both parameters must be defined by the project developers at the start of the study. The parameters can be linked by the equation of Dupuit (1863):

$$Q_i = 2\pi k_f H_0 \frac{s}{\ln \frac{R}{r}} \tag{2}$$

with Q_i being the flow rate of the well [m^3/s], k_f the coefficient of hydraulic conductivity [m/s], H_0 the thickness of the aquifer [m], s the drawdown [m], R the reach of pressure drop [m], and r the diameter of the well [m] within the target formation.

For this study, Eq. (2) is used to determine the hypothetical flow rate for each of the analysed wells as if they were drilled exactly as the planned well. Therefore, the k_f used in Eq. (2) is the hydraulic conductivity of the analysed well, while the aquifer thickness H_0 and drawdown s take on the values of the new well.

The following equation can be used for estimating the reach of the pressure drop according to Sichardt (after Hölting and Coldewey, 2009):

$$R = 3000 s \sqrt{k_f} \tag{3}$$

even though the units on both sides of this empirical equation do not match.

Hydraulic conductivity is thus the only parameter that has to be determined by analysing the wells surrounding the planned project. k_f can be calculated by the following equation (Hölting and Coldewey, 2009):

$$k_f = k \frac{\rho_f}{\nu_f} g \tag{4}$$

with k being the average permeability of a well [m^2], ρ_f the density of the fluid [kg/m^3], ν_f the viscosity of the fluid [Pa s] and g the acceleration due to gravity (9.81 m/s). Often the fluids encountered in deep aquifers are brines depending on the lithology (e.g. Wolfgramm et al., 2011; Stober et al., 2014), which – together with the higher temperatures – has a strong influence on the fluid's density as well as viscosity. It is, therefore, important to obtain reliable data on water chemistry and temperature. However, studies have shown that the influence of temperature on viscosity is negligible compared to the variations in permeability for the temperature ranges typically analysed (10-15 K) (Birner et al., 2013). Accordingly, the impact of the fluid's density or viscosity on the final results is much smaller than that of the permeabilities used for the calculation.

4.2. Correlation between porosity and permeability

4.2.1. Correlation functions

The problem of characterising the hydraulic properties of an aquifer for which an insufficient amount of hydraulic tests is available has spurred various approaches to calculate permeability from porosity (Nelson, 1994). In this paper, we concentrate on two different approaches used for Rhaetian sandstones. One approach (e.g. Mathiesen et al., 2011; Kristensen et al., 2016) is the adaptation of the Kozeny equation (Kozeny, 1927):

$$k = a\phi^b \tag{5}$$

with a and b being coefficients determined by fitting the function to the actual dataset and ϕ being the porosity. For different reservoirs, different correlations between porosity and permeability have been developed. For the sandstones from the Gassum, Bunter and Haldager formations in Denmark, Mathiesen et al. (2011) propose the following equation:

$$k = 196449\phi^{4.3762} \tag{6}$$

with ϕ being the dimensionless porosity [–]. Kristensen et al. (2016) propose a slightly different equation for the sandstones of the Gassum formation alone:

$$k = 4.43 \cdot 10^{-4} \phi^{4.36} \tag{7}$$

with ϕ being porosity in percent [%]. However, the authors stress that this equation should be adapted to a local reservoir by introducing an additional constant multiplication factor determined from local core analysis data.

The second approach is based on considerations of the fractal nature of pore spaces within sandstones (Pape et al., 1999). Pape et al. (1999) have developed equations of the form:

$$k = A\phi + B(\phi)^2 + C(10\phi)^{10} \tag{8}$$

where A, B, and C are empirical parameters for different types of rocks from sandstones to shales mainly in the NGB and φ is the porosity in percent [%]. The form of Eq. (8) is based on theoretical considerations regarding fractal pore-space geometry and was calibrated with core measurements of porosity and permeability from various formations in the NGB. Pape et al. (1999) kept the ratio of A, B and C essentially the same (1:241:6) for all the equations they derived for the different formations and rock types.

As the Gassum formation is the Norwegian–Danish equivalent of the Rhaetian formation in the NGB, the approach by Kristensen et al. (2016) can be compared to the approach by Pape et al. (1999) on the data set of a hypothetical project in the NGB.

4.2.2. Calculation of correlation functions

In order to find the best correlation function either based on Eq. (5) or (8), each data point has been considered to be of the form:

$$k = \phi^c \tag{9}$$

with c being the exponent necessary to achieve the permeability based on the porosity. The best-fit was achieved by minimising the differences in exponents via the least-squares approach:

$$\min \sum (c_r - c_m)^2 \tag{10}$$

with c_m being the exponent of the measured data and c_r the exponent of the best-fit curve for the respective data point. Therefore, for the best-fit the following expression was minimised:

$$\sum (\log k_r - \log k_m)^2 \tag{11}$$

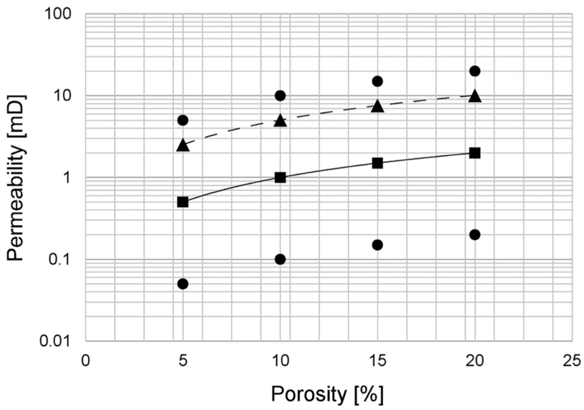

Fig. 3. Comparison of two methods to find the best correlation function for hypothetical data. Dots: data to be fitted; squares with solid line: correlation function based on Eq. (11); triangles with dashed line: correlation function based on Eq. (12).

with k_r being the calculated permeability [(nm)^2] of the correlation function, k_m the measured permeability [(nm)^2], and ϕ the measured porosity [–]. This differs from the commonly used equation, in which:

$$\min \sum (k_r - k_m)^2 \tag{12}$$

but which does not take the logarithmic nature of the permeability data into account as shown in Fig. 3. Eq. (11) is thus used to achieve the best correlation function.

4.2.3. Kozeny–Carman equation

Correlation functions can overestimate permeabilities for high porosities. In order to attain more realistic values for permeability in such cases, the correlation function is combined with the Kozeny–Carman equation:

$$k = \frac{0.2\phi^3}{S^2(1-\phi)^2} \tag{13}$$

with S being the specific surface area of the rock matrix [m^2/m^3] (Ungerer et al., 1990). Combination of the Kozeny–Carman equation with the correlation function means that permeabilities are calculated using both functions separately but that the lower permeability value is always used for further analysis. For aquifers with low porosities, the limiting use of the Kozeny–Carman equation might even be superfluous.

4.3. Determination of aquifer thickness

It is necessary to analyse gamma-ray (GR) and spontaneous-potential (SP) logs in order to estimate the thickness of the aquifer (input parameter for Eq. (2)) and determine the zone within the formation where total porosities and permeabilities can be estimated from well log data. Fig. 4 shows a typical GR log response of a fluvial sandstone of Rhaetian age in the NGB. The sandstone can be clearly identified by low GR readings compared to those of the clay-rich sediments above and below this interval. The position of top and bottom as well as the resulting thickness of this sandstone can be directly read from the depth scale. Only log data of this sandstone interval would be used to estimate the hydraulic properties for this site. This process will be explained in Section 4.4.

If no GR log is available, an SP log can be used for the identification of the sandstone layer. The use of either GR or SP logs for this correlation is possible as the response of SP is similar to that of the GR measurements for porous sandstones as well as shales, the only rock types encountered in the studied reservoir. In different reservoirs with different lithologies, GR logs should be used as the sole tool to identify sandstones.

For most geothermal projects, seismic data are analysed prior to a POS study and are valuable to identify the structural setting, the position and the thickness variation of a potential aquifer. However, due to decreasing resolution with depth, their significance with regard to the actual thickness of the usable sandstone unit in depths of more than 1000 m is limited. In particular, seismics cannot resolve thin layers of clay, which still may represent an effective hydraulic seal between two permeable sandstone layers.

4.4. Hydraulic data from log measurements

In order to acquire sufficient information about the hydraulic properties of the reservoir, subsidiary data in the form of borehole logs are analysed. Sonic logs are the most prevalent, while the number of density or neutron logs is limited. However, information about total reservoir porosity is not readily given by either log measurements but has to be calculated.

In case of the sonic log, the following equation according to Wyllie et al. (1956) can be employed in order to obtain the total reservoir porosity:

$$\phi = \frac{t_{\mathrm{Log}} - t_m}{t_f - t_m} \tag{14}$$

with t_{Log} being the measured interval travel time of the sonic wave [μs/m], t_m the interval travel time in the rock matrix [μs/m], and t_f the interval travel time in the formation fluid (e.g. water and/or gas) [μs/m].

In case of a litho-density log, the total porosity can be calculated from the measured densities:

$$\phi = \frac{d_m - d_{\mathrm{Log}}}{d_m - d_f} \tag{15}$$

with d_m being the density of the matrix [kg/m^3], d_{Log} the measured bulk density [kg/m^3], and d_f the density of the formation fluid (e.g. water and/or gas) [kg/m^3]. The parameter values used in Eqs. (14) and (15) are given in Table 1.

The main purpose of the neutron log is the determination of a formation's total porosity. The neutron log is calibrated to read total porosity directly in a limestone matrix. To read total porosity in any other lithology (e.g. sandstones), it needs to be corrected by using correction charts. As the neutron log is sensitive to the hydrogen concentration in the formation, several effects (fluid density, amount of shale in the formation, hydrocarbon effect) are controlled to estimate the total porosity (Serra, 1986). A method to correct the neutron log by the amount of shale is described in Dewan (1983).

With the correlation function determined beforehand, permeabilities can then be calculated from the total porosities derived from the log as well as from single effective porosity core measurements.

5. Application to the model case

5.1. Location

The model case for which this method is demonstrated is located at a site between Lüneburg and Schwerin in Germany. Here, the depth of the Rhaetian is about 3040 m below surface according to the Geothermal Information System for Germany (www.geotis.de) (Agemar et al., 2014, 2018). In case of a real project, this depth would be verified by seismic measurements before commissioning a POS study. The Contorta sandstone of the Rhaetian has been chosen as the target.

Due to issues of data confidentiality, the case study cannot present a model case which is identical or close to an existing well.

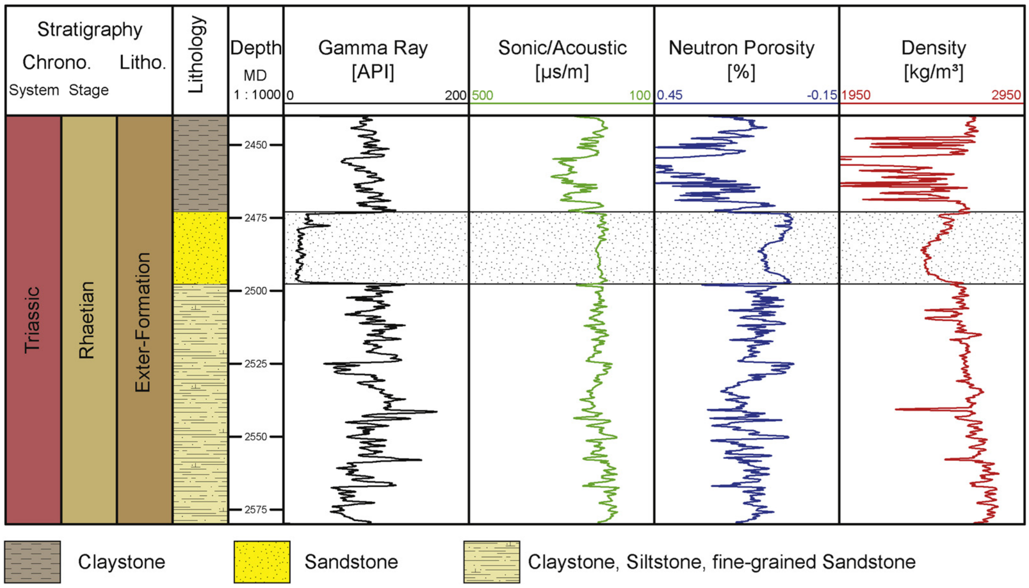

Fig. 4. Schematic drawing of the correlation between gamma-ray and density log. Total porosities within a typical fluvial Rhaetian sandstone can be identified.

Table 1
Parameter values used in Eqs. (14) and (15).

	Travel time (µs/m)	Density (g/cm^3)
Sandstone matrix	182	2.65
Formation fluid (water)	620	1
Formation fluid (gas)	3018	0.2

5.2. Temperatures

The site is located more than 2.5 km from the nearest salt intrusion. Therefore, the higher thermal conductivity within the salt and the subsequently raised temperatures above the salt should have a negligible effect on the temperatures at the chosen hypothetical site. Within a radius of 50 km, 39 wells with temperature measurements reach a depth of 3040 m or more. 22 of these wells are located very close to a salt intrusion (less than 500 m) and it is possible that their thermal profile is influenced by this. These wells and all wells directly above a salt intrusion are assigned a weighting factor of 1, while the other wells, whose thermal profiles are more likely representative of the project site, are assigned a weighting factor of 2. The influence of this choice of weighting factors is shown in Table 2. While for five wells a continuous log is available, temperature data for the remaining wells consist solely of BHT measurements.

Ideally, more than 20 wells should be used to calculate the POS to achieve a statistically significant number of samples. As in this example this number is surpassed by nearly a factor of 2, the results are thought to give a good indication of expected temperatures at the site of interest.

Table 2
Probabilities of success for two temperatures and different weighting factor scenarios.

	A	B	C
POS_{105} [%]	61.5	69.1	79.1
POS_{108} [%]	53.8	53.8	61.7

The temperatures used are 105 °C (POS_{105}) and 108 °C (POS_{108}). Column A: only the number of wells reaching this temperature is considered; column B: the distance of the wells to the planned site is considered; column C: the distance as well as a weighting factor of 2 for wells in a comparable geologic situation are considered.

5.3. Hydraulic data

In order to have a sound statistical base for the calculations of hydraulic properties, which can vary significantly from well to well, more than 50 wells should be used. A larger number is desirable, but a trade-off of between a sufficient number of wells and only using wells in the immediate surroundings of the planned site has to be made. Moreover, the geology of the target formation also plays a role. In case of fluvial sandstones, it is good practice to employ an elliptical search area, which is oriented along the direction of the paleo-fluvial system. An ellipse was created with a semi-minor axis representative of the width of the channel system (60 km) and a semi-major axis (120 km), which was oriented along the paleo-flow direction and included the last wells thought to be part of the main channel system before it transformed into the delta front and prodelta.

Within this ellipse, 61 wells are located which provide hydraulic data for the target formation. The exact numbers of data sets are given in Table 3. Some wells had only a single core measurement of porosity, while most wells had combinations of core measurements and logs.

In case of hydraulic tests, the indicated permeabilities can be directly used in Eq. (4) to calculate the hypothetical flow rate for the analysed well. However, often more than one test was performed per well, always resulting in different permeabilities, which could vary by an order of magnitude. In these cases, the arithmetic mean of the permeability was computed and used in Eq. (4). This was necessary as only one value of hypothetical flow is applicable for Eq. (1) (POS).

Core measurements of both porosity and permeability were available for four wells. These data are plotted in Fig. 5.

5.4. Correlation functions

Four different correlation functions were determined for the data set shown in Fig. 5. Functions 1 and 2 are based on Eq. (8), but, while function 1 retains the coefficients' ratio of 1:241:6 as given by Pape et al. (1999), function 2 has no such underlying restriction (see Table 4, in which the coefficients of all correlation functions are given). Functions 3 and 4 are based on Eq. (5). While function 3 keeps the exponent to 4.36 as detailed in Kristensen et al. (2016), the exponent in function 4 is chosen to provide the best fit to the core measurements. As can be seen from the least-square residues (Table 4), functions 3 and 4 fit the data nearly equally well, while the difference between functions 1 and 2 is larger. All correlation functions however achieve a good fit.

Table 3
Number of wells with data sets for a given type of measurement and total number of measurements available for a given type of measurement for the model case.

	Hydraulic tests	Core measurements		Well logs		
		Porosity	Permeability	Neutron	Density	Sonic
Number of wells	2	31	4	0	2	31
Number of measurements	21	992	173			

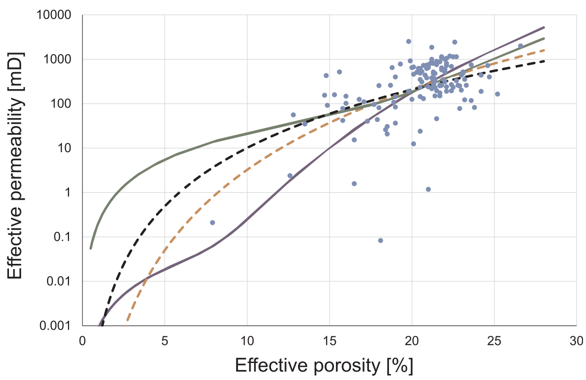

Fig. 5. Fits of four correlation functions to measured data. Blue dots: core measurements; purple curve: function 1 (based on Eq. (8)); green curve: function 2 (based on Eq. (8)); dashed black curve: function 3 (based on Eq. (5)); dashed orange curve: function 4 (based on Eq. (5)). For details of functions see Table 4.

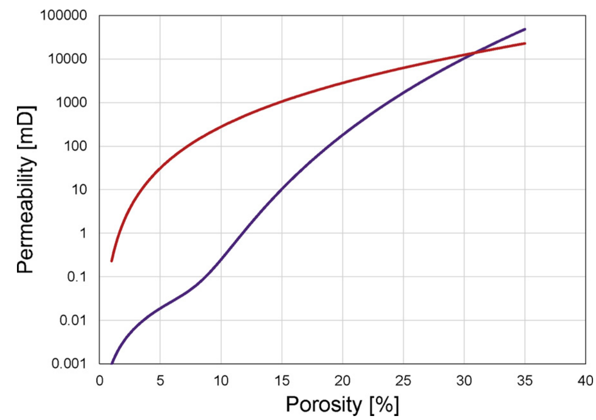

Fig. 7. Permeability functions used for analysis. Purple line: function 1; red line: Kozeny–Carman equation. Only the lower permeability values of both equations are used for further analysis.

Table 4
Coefficients for Eqs. (5) and (8).

	After Pape et al. (1999)			After Kristensen et al. (2016)		Least-squares residue
	A	B	C	a	b	
Function 1	28.1	6761.5	173.0			103.1
Function 2	0	2171616.1	91.7			89.6
Function 3				$4.43 \cdot 10^{-4}$	4.36	28.2
Function 4				$3.15 \cdot 10^{-6}$	6.01	26.7

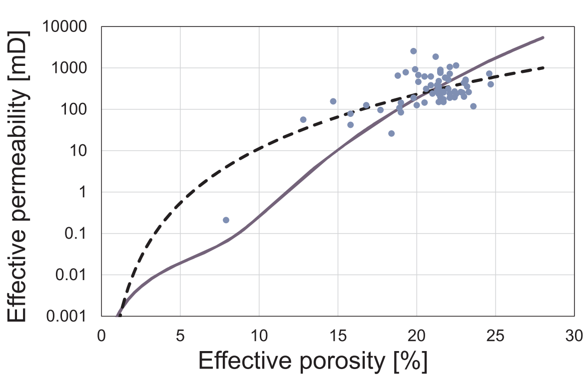

Fig. 6. Example of correlation functions for one specific well. Blue dots: core measurements for one well; purple line: function 1 fitted for one specific well; dashed black line: function 3 fitted for one specific well. Coefficients of functions 1 and 3 differ from Table 4.

If there is a sufficient number of core measurements of effective porosity and permeability for one well for which log data is also available, a specific correlation function for this well is determined (Fig. 6). With this approach, the permeabilities calculated from the total porosities derived from log data of this well are as close as possible to the core measurements data. The large variations in effective permeability within a single well can be explained by changes in sedimentation, e.g. clay content and variations in grain size distribution or diagenetic effects from bottom to top of the sandstone formation.

5.5. Kozeny–Carman equation

In this case study, correlation functions based on Eq. (8) tend to overestimate permeabilities for porosities larger than about 25%. Therefore, function 1 is combined with the Kozeny–Carman equation (Eq. (13)). S is assumed to be 30,000 [m^2/m^3] for the studied sandstones (Rabbani et al., 2014). Fig. 7 indicates that in this case the threshold for using the Kozeny–Carman equation is at about 31% porosity. However, for a different data set with a different correlation function, this threshold may be significantly lower.

5.6. Determination of aquifer thickness

In the vicinity of the hypothetical project site, well logs for several wells are available, but their spatial distribution is highly variable. In combination with the heterogeneously deposited sediments of the fluvial system, determination of the aquifer thickness is non-trivial. Fig. 8 shows two possible approaches, for which all wells have been used which are located in the vicinity and within the same fluvial channel as the hypothetical project site and which possess information about aquifer thickness. If the aquifer thickness is likely to change significantly over short distances (see Fig. 8b, top right corner) and the data coverage is not optimal as in our case, the combination of various methods leads to a more robust estimate of the aquifer thickness than a single method. Here, the aquifer thickness has conservatively been estimated to be 30 m, thus being on the lower range of possible values. The influence of higher or lower aquifer thicknesses on the POS is ideally determined by a sensitivity analysis (see Section 6.5).

5.7. Results

For the hypothetical project a depth of 3040 m below ground and an estimated aquifer thickness of 30 m for the Contorta sandstone of the Rhaetian formation have been used for the POS calculations. The results

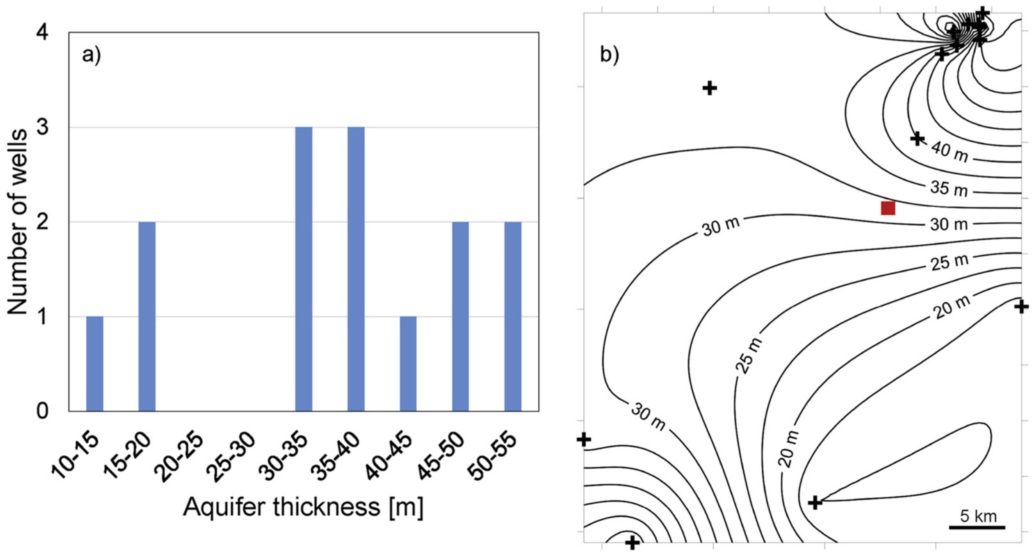

Fig. 8. Determination of usable thickness of Contorta sandstone. (a) Histogram showing the number of wells whose aquifer thicknesses fall within the indicated ranges; (b) geostatistical interpolation via kriging. Black crosses: wells with information about aquifer thickness; red square: location of hypothetical project. The map is oriented towards north.

Table 5
The probabilities of success for reaching different parameters.

Temperature [°C]	POS_T [%]	Flowrate [l/s]	Drawdown [m]	POS_H [%]	POS_{total} [%]
105	79.1	25	300	68.1	**53.9**
105	79.1	30	300	63.2	**50.0**
108	61.7	25	300	68.1	**45.7**
108	61.7	30	300	63.2	**42.4**

POS_T: POS of reaching given temperature; POS_H: POS of reaching given flowrate and drawdown; POS_{total}: POS of reaching all parameters.
The bold values are the results of summation or multiplication of other columns in the table.

are shown in Table 5. The POS for reaching or surpassing a given temperature and combination of flowrate/drawdown at the same time are given in the last column. According to statistics, the probabilities of two independent events are multiplied. Thus, in order to achieve a high POS for the whole project, the separate POS values for temperature and hydraulic properties should be close to 100%.

For the results in Table 5, distance weighting has been used for temperatures as well as for hydraulic properties. An additional weighting factor of 2 has been used for temperatures to differentiate between wells probably influenced by salt structures and those which are not. No additional weighting factors with regard to data quality have been used for the hydraulic properties.

To gain a better spatial understanding of the discussed parameters, the distribution of wells which do or do not achieve the required parameter values has been mapped (Figs. 9 and 10).

Fig. 10 shows that the hypothetical project site is located in a transition zone between predominantly good hydraulic conditions to the northeast and less suitable conditions to the southwest of the area. This distribution reflects the direction of the fluvial system, with sediments becoming progressively finer and probably less porous towards the distal part of the delta system.

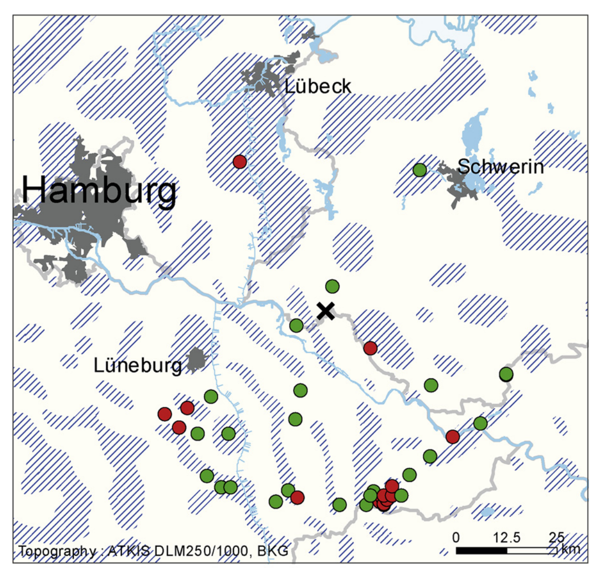

Fig. 9. Thermal properties of wells in the vicinity of the hypothetical project (black cross). Green dots: wells reaching at least 105 °C in 3040 m depth; red dots: wells not reaching 105 °C in 3040 m depth. Dashed areas: salt structures (Reinhold et al., 2008).

6. Discussion

6.1. Data quality

6.1.1. Bottom-hole temperatures

Bottom-hole temperatures tend to show significantly lower values than real reservoir temperature due to the fact that BHTs are recorded shortly after drilling in a borehole cooled down by drilling mud. Various attempts have been made to correct BHTs (e.g.Wilhelm, 1990; Förster, 2001), but the results indicate that corrected BHTs still differ by several degrees from reservoir temperatures. In the context of a POS study, this means that the chances of a planned project to reach a certain temperature threshold are probably underestimated. This satisfies the inherent condition of insurance companies to judge projects conservatively. However, it also poses the risk that a promising project will not be realised as the calculated POS is not high enough for a potential investor.

BHTs also prohibit the inclusion of shallow wells into the statistics.

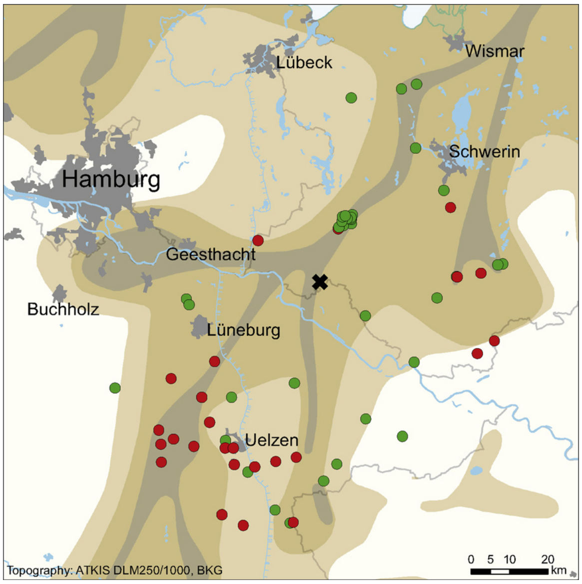

Fig. 10. Hydraulic properties of wells in the vicinity of the hypothetical project (black cross). Green dots: wells reaching a combination of at least 25 l flowrate with 300 m drawdown for the Contorta sandstone; red dots: wells not meeting the requirements. Background: thickness of Rhaetian sandstones (Franz et al., 2015). Light brown: 0–10 m thickness; medium brown: 10–20 m thickness; grey: 20-50 m thickness.

To do so, temperature profiles of shallow wells would have to be extrapolated up to the required depth. However, if the bottom-hole temperature in 1000 m depth is 3 °C too low, an extrapolation to a depth of 3000 m would increase this to 9 °C below real reservoir temperature. Therefore, wells with only BHT measurements which are shallower than the required aquifer depth should not be taken into account for the POS calculation.

6.1.2. Types of measurements

Hydraulic tests are thought to provide the best information on the hydraulic properties of the aquifer as they integrate over a larger interval of several meters, i.e. reservoir scale, and are not selective measurements over a few centimeters as in cases of core measurements. However, the available data show that repeated testing of the same interval produces permeabilities which vary by up to one order of magnitude; a variability which may be caused by different testing durations. This is an indicator for the large heterogeneity of the Rhaetian sandstones, which poses a challenge to correctly determine the hydraulic properties of the aquifer.

In the absence of hydraulic tests, core measurements or logs are used to determine the hydraulic properties of the reservoir. Due to the small size of the plugs compared to the reservoir dimensions, core measurements tend to provide only a very localised information, which cannot necessarily be extrapolated to the whole reservoir. Logs on the other hand are available for the entire thickness of the reservoir but do not provide first-hand information on hydraulic properties. Accordingly, porosities derived from logs are associated with a higher uncertainty than porosities directly measured at core plugs. Moreover, porosities derived from logs are total porosities and not effective drainage porosities. Thus, permeabilities derived from these porosities tend to be higher than those from hydraulic tests.

For the Rhaetian sandstones analysed in this study, permeabilities derived from logs tended to be a factor of two higher than permeabilities from core measurements. Given the large natural variation of permeabilities within these sandstones, this variation is acceptable. However, for different sandstones in different locations, care should be taken about using log measurements if the discrepancy between total and effective porosity is much higher than in the example presented here as it would lead to an overestimation of hydraulic properties.

6.2. Correlation function

Establishing a correlation function for porosity and permeability is affiliated with large uncertainties as the measured permeability for a given porosity can vary by several orders of magnitude. However, two approaches have been shown to produce satisfying results. The first approach by Pape et al. (1999), based on theoretical considerations about pore space geometry, enables to calculate a correlation function for the whole range of porosities encountered. The second approach by Kristensen et al. (2016) only works well if the available data are clustered either towards high or low values. For the case study discussed in this paper, Eq. (5) yields better results than Eq. (8) with respect to minimising the difference between measured values and the correlation function (see Table 4).

In this context, it is also important to keep the general purpose of the correlation function in mind. It should provide a correlation between porosity and permeability for the aquifer in question so that measured porosity values can be converted into permeability values. This requires a function which covers the whole range of porosities equally well. As such, Eq. (8) is more versatile than Eq. (5) as it has not been developed for a specific formation and also allows for establishing a general correlation function for the whole data range.

The implications of using either correlation function for calculating the POS are determined by their intersection point. For our case study, the correlation functions 1 and 3 (Table 4) intersect at about 20.5% porosity. Therefore, if the required flowrate/drawdown combination for an economically feasible project translates to required porosities lower than this value, correlation function 3 (Kristensen et al., 2016) gives higher POS, for values higher than 20.5%, correlation function 1 (Pape et al., 1999) predicts higher POS.

Even though Pape et al. (1999) provide correlation functions not only for Rhaetian sandstones but also for example, Fontainebleau sandstones, it is recommended to test different correlation functions for different kinds of sandstone. This ensures that the best data fit is achieved. Apart from Pape et al. (1999) and Kristensen et al. (2016), whose correlation functions may be adapted to other types of sandstone, further correlation functions are given by Nelson (1994).

We have examined data from the Rhaetian formation in the NGB for wells where hydraulic tests can be compared to other measurements in order to assess the quality of the correlation function. Our results show that the differences between permeabilities from hydraulic tests and other measurements are usually within one order of magnitude. Wolfgramm et al. (2008) find that permeabilities from hydraulic tests are about a factor of 2 higher than those from cores. Given that permeabilities within one well can vary much more (Fig. 6), this result indicates that even though hydraulic tests are the most reliable data source, permeability values derived from logs can also be used. However, given the low number of wells for which we can compare the data so far, more specific conclusions cannot be drawn.

It should be pointed out that the correlation functions used here only yield a reliable representation of the hydraulic properties if the transport within the reservoir is not fracture-dominated but relies only on flow through connected pore space. Otherwise, core measurements significantly underestimate the hydraulic conductivity of the reservoir as they do not include the large fractures, which are responsible for most of the hydraulic transport in these cases.

6.3. Weighting factors

In case of very heterogeneous data, weighting factors are useful to compensate for differences in e.g. geological setting. However, they should be used with care as they can change the result of the study significantly. This is especially problematic as for most weighting factors no strict mathematical or physical background exists and the value of the weighting factor is chosen arbitrarily.

6.3.1. Temperature

As in Eq. (1) $1/r$ is used, wells in close vicinity of the planned site are not given too much weight in the calculations. This is especially important in areas with a very heterogeneous data coverage. As an additional effect, other weighting factors can have a significant impact on the results. This is evident in Tab. 2, where weighting due to geology has much more influence on the POS than distance weighting.

In the NGB, weighting according to geological differences in the location of wells is necessary to account for the influence of salt structures on temperatures. As salt has a significantly higher thermal conductivity than the surrounding sediments, salt structures disturb the local thermal field. A weighting factor of 2 for wells which likely experience the same thermal field as the planned well (either disturbed or undisturbed) takes these differences in geological setting into account.

6.3.2. Hydraulics

In case of hydraulic properties, introducing weighting factors based on different geological settings into the POS calculation is difficult. It would require reliable information on the geologic setting relevant for the hydraulic properties (e.g. channel or not) for all wells. This information is not available for the NGB even though the work of Franz et al. (2018b,a) is a first and important step into this direction.

Using weighting factors to account for different data quality (logs versus core measurements of porosity and permeability versus hydraulic tests) is also a challenge. As hydraulic tests are representative of the whole aquifer, their results are thought to be the best information on the hydraulic properties of a given layer and should be given the highest weighting factor. However, this superiority over other data cannot be quantified and choosing weighting factors to balance different data sources is not an exact method. The influence of different weighting factors on the POS of the case study is listed in Table 6.

In our case study, the introduction of weighting factors for data quality leads to a reduction of the POS. However, this is not a general rule and is strongly case-dependent. Naturally, the higher the weighting factors, the more pronounced the differences in POS.

6.3.3. Distance weighting

In our example, we have used distance weighting to account for the fact that conditions in wells closer to the planned site are probably more indicative of the conditions of interest than those of wells farther away. This type of distance weighting only takes the horizontal distance between wells into account.

However, an additional type of distance weighting should be introduced if the necessary data are available. In this case, the maximum burial depth of the aquifer of interest is the decisive factor. As the maximum burial depth influences the porosity and thereby also the permeability, wells which experienced a similar burial history as the planned well should factor higher in the calculation of the POS. This could be realised by employing a vertical distance weighting, in which the maximum burial depths of the wells are taken into account. However, as the maximum burial depths for the aquifers in the NGB are only locally known, this information could not be considered on the broad regional scale used for this study.

For this reason, the horizontal distance weighting will be regarded as a proxy based on the assumption that wells closer to the planned site more likely experienced a similar burial history than wells farther away.

Table 6
Influence of different weighting factors on the probability of success (POS).

	Data quality weighting factors				
	A	B	C	D	E
Logs	1	1	1	1	1
Porosity from core	1	1	1.1	1.33	2
Permeability from core	1	1	1.5	1.67	3
Hydraulic test	1	1	2	2	4
POS	**59.0**	**68.1**	**60.8**	**54.0**	**39.0**

A flowrate of 25 l/s and a drawdown of 300 m are used. Column A is based only on the number of wells reaching or surpassing the parameter combination, columns B to E also include weighting due to distance of wells.

6.4. Diagenesis

The general assumption of targeting sandstone layers of the Rhaetian as aquifer is that thick deposits of clay-poor or clay-free sandstone yield permeabilities high enough for an economical geothermal project. However, data show that certain wells exhibit porosities and permeabilities close to zero even though they were drilled through thick and clay-free sandstone deposits. In case of the wells Allermöhe 1 and Neuruppin GT/Nn 1/88 (both not part of our case study), analysis indicates a cementation of the pore space with anhydrite due to episodic high-temperature flows from lower-lying reservoirs (Wagner et al., 2005). Our research identifies other wells with close to zero porosities which have not been examined so far. The reason for their low-permeability reservoirs is unknown and in addition to high-temperature flows along fault structures, other diagenetic processes may have led to the cementation of the reservoirs' pores.

Thus, diagenetic processes present an incalculable risk for the determination of the POS of a project. As diagenetic overprinting of the reservoir is impossible to detect before drilling, it has not been factored into the calculations presented in this paper. Therefore, a well with a high probability of success might nevertheless be unsuited for a geothermal project.

To reduce the risk of drilling a well into a diagenetically overprinted reservoir, for example, seismic measurements can be employed to search for deep-reaching fault structures close to the planned site. According to Wagner et al. (2005), the effects of high-temperature flows from lower-lying reservoirs into the aquifer along a fault are restricted to the immediate vicinity of the fault (less than 100 m). Hence, relocating the planned well by a few hundred meters in case of a detected deep-reaching fault may reduce the risk due to diagenetic overprinting significantly.

6.5. Sensitivity analysis

Even though the input parameters for a POS study are defined by the project developers (required temperature and flowrate/drawdown combination) or are given by the local geology (depth and thickness of aquifer), a thorough study should always comprise a sensitivity analysis, which should be much more detailed than the few parameter combinations shown in Table 5. For one thing, it enables the developers to optimise project planning as higher temperatures than expected can compensate a lower flowrate or vice versa. These aspects have to be reflected in the planning of the geothermal plant. However, more importantly a sensitivity analysis also helps to put the inherent uncertainties into perspective. Ideally, the results of the sensitivity analysis show that the POS for the parameter range of interest does not change much. For example, the flowrate/drawdown should stay (nearly) constant if the aquifer thickness is reduced by a few meters. If not, this is an indicator for a very heterogeneous reservoir and the associated higher exploration risk. In our test case, the POS does not change for aquifer thicknesses between 27 m and 33 m.

Given the statistical nature of the method, small changes in the parameter values can lead to rather large changes of the POS. This is especially true if only a small number of wells is used. Accordingly, a higher number of used wells generally results in a smoother POS distribution. As an example, Fig. 11 shows the POS distribution for varying

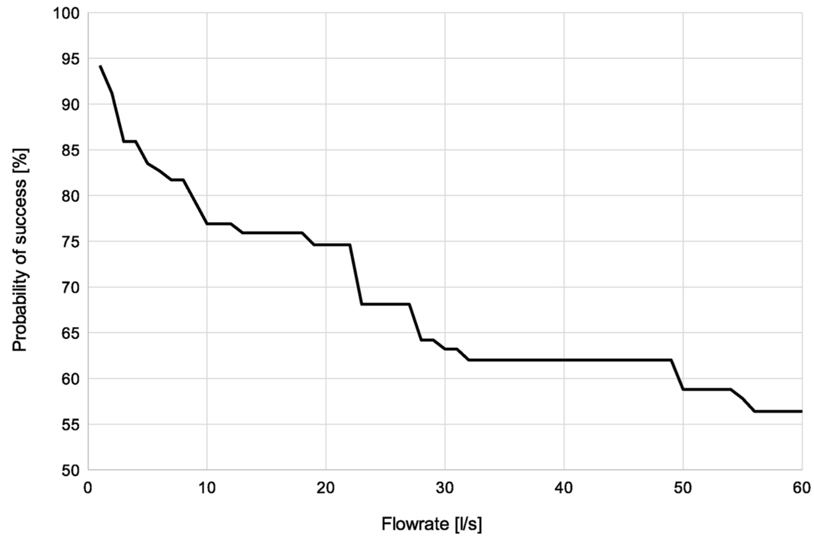

Fig. 11. Probability of success for varying the required flowrate assuming 300 m drawdown and 30 m aquifer thickness.

the required flowrate (assuming 300 m drawdown and 30 m aquifer thickness) and the discontinuities inherent to the method.

7. Conclusions

A POS study provides project developers with much needed insight into the chances of realising an economically successful project, i.e. reaching or surpassing temperature and hydraulic values needed for an economically sufficient energy output of a well. As the chances are quantified and a sensitivity analysis for single parameters can be performed, the planning of the project can be optimised and – if necessary – insurances against an insufficient energy output of the well obtained.

The method described in this paper has been developed for sandstone aquifers in the North German Basin but can be extended to any porous, not fracture-dominated aquifer worldwide. As the method allows the utilisation of all types of hydraulic data, including porosity values derived from well logs, it can even be applied in areas where high-quality hydraulic data such as hydraulic tests are sparse or non-existing.

Even though the newly developed method does not rely on hydraulic tests, they are still the most reliable data to characterise the hydraulic properties of an aquifer and should be used if possible.

Various functions to correlate porosity and permeability are available, but for each aquifer under consideration, the correlation function which achieves the best fit has to be identified. For Rhaetian sandstones and the purpose of this study, a correlation function based on Pape et al. (1999) is the best choice.

Using a statistical approach, a POS study depends on the availability of a sufficient amount of subsurface data to achieve reliable results. It is therefore restricted to areas where past exploration for example, hydrocarbons has generated information on temperatures and hydraulic properties. Given the statistical nature of the method and the variability of the data, fifty wells with hydraulic data and twenty wells with thermal data are considered to be the necessary minimum for a reliable POS study.

The method presented in this paper provides a basic scheme that should be improved for individual cases depending on the available database. Possible improvements may be for example more sophisticated data weighting procedures than presented here or the introduction of a depth correction for input data measured in different depth ranges. For the optimisation of POS studies, analysis of additional information to also account for potential diagenetic overprinting of the reservoir is necessary.

Using all available subsurface information, a POS study provides a data-based geological risk analysis, which can be used complementary to a feasibility study.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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