Reservoir prediction and risk assessment of hydrothermal reservoirs in the North German Basin – combining deep subsurface reservoir mapping with Monte-Carlo Simulation

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ABSTRACT

The development of Mesozoic hydrothermal reservoirs in the North German Basin requires precise prediction of reservoir qualities as well as reliable assessments of the exploration risk in order to insure stakeholders and financial partner against the geological risk. So far, the risk assessment by means of so-called Probability of Success (POS) studies employed only mathematical methods to derive probabilities of reservoir thicknesses, fluid temperatures and productivity indexes. This has resulted in mismatches of reservoir parameters proposed by POS studies before drilling and reservoir test data measured after drilling. Here, we present an approach combining sedimentological and mathematical methods to enable more realistic assessments of the exploration risk. For a potential geothermal site in western Mecklenburg-Vorpommern (Germany), where the development of a Rhaetian (Triassic) hydrothermal reservoir at a depth of about 2800 m is planned, the risk assessment was done combining results of subsurface reservoir mapping and Monte Carlo Simulation (MCS). Compared to ordinary Kriging, the herein applied approach results in more realistic distribution pattern of reservoir thicknesses and, consequently, enable more reliable risk assessments of flow rates and productivity indexes.

1. INTRODUCTION

In Northern Germany, hydrothermal reservoirs (Rhaetian sandstones) are operated by municipal suppliers for district heating since the late 1980s. The long-term economically successful operation of hydrothermal reservoirs requires a minimum productivity index of 50 m^3 $(h \times MPa)^{-1}$. Such a high production rate is directly related to high-reservoir quality, mainly the effective reservoir thickness (net-thickness) and permeability. Based on the experiences in long-term operation, a hydrothermal reservoir should have >65 °C reservoir temperature, >20 m net-thickness and >500 mD permeability (Rockel et al. 1997).

For the risk assessment of a potential geothermal site, neighbouring wells, seismic data and literature data are evaluated. Employing stochastic and statistic methods, these data are commonly employed to perform a geological model to enable predictions of reservoir qualities. But in most cases, the wells are located within a great distance to the potential site, seismic data do not penetrate the target zone and/or may only provide rough depth estimations. The geological model, however, is used for reservoir quality modelling, in particular the productivity index, and economic calculations. Furthermore, it is often demanded to estimate the probability of certain reservoir parameters. For this, a Monte Carlo Simulation (MCS) is commonly used (e.g. Goumas et al. 1999, Lukawski et al. 2016).

Recent advances in deep subsurface reservoir mapping of the North German Basin revealed a close relation of high-quality sandstone reservoir and certain depositional environments. For the Rhaetian Deltaic System, Franz et al. (2018) have shown that high-quality reservoirs can only be found within narrow distributary channel belts. Due to this and high lateral variations of reservoir qualities a comprehensive knowledge of the depositional environment and its primary sedimentation processes is needed to ensure reliable reservoir predictions (Franz et al. 2018). Here, we present a combined approach of deep subsurface reservoir mapping and MCS resulting in improved reservoir prediction and risk assessment.

2. GEOLOGICAL SETTING AND LOCATION OF THE HYPOTHETICAL GEOTHERMAL SITE

The Central European Basin (CEB), a large epicontinental sag basin (e.g. Bally and Snelson 1980, Bachmann and Grosse 1989, Ziegler 1990), initiated in the Late Carboniferous and has been active up to recent times. During this long time span, an up to 10,000 m thick basin fill accumulated, with the greatest thickness in the North German Basin (NGB). Considering its thick basin fill and geothermal gradients of 32–90 K per km of depth, the North German Basin yields enormous geothermal resources (Wolfgramm et al. 2014). According to Jung et al. (2002), about 96% of the total geothermal resources are bound to so-called petrothermal reservoirs which require stimulation techniques to be developed (Enhanced or Engineered Geothermal Systems: EGS), 4% are bound to faults and only 1% is bound to hydrothermal reservoirs which can be exploited by, for example, conventional Doublet systems (Franz et al. 2018). But so far, only hydrothermal operations have been economically successful in the North German Basin.

Previous studies have identified six complexes of hydrothermal reservoirs in the Mesozoic succession of the North German Basin: (1) Middle Buntsandstein; (2) Lower–Middle Keuper; (3) Upper Keuper; (4) Lower Jurassic; (5) Middle Jurassic; and (6) Lower Cretaceous (e.g. Katzung 1984, Beutler et al. 1994, Schulz and Röhling 2000, Franz et al. 2015). For this study, an exploration example of the Upper Keuper reservoir complex was selected. The proposed drilling site is located in the westernmost part of the federal state of Mecklenburg-Vorpommern in the vicinity of Lower Saxony in the South and Schleswig-Holstein in the West (coordinates in Table 1). The exploration database comprises five deep wells which have penetrated the exploration target (Table 2).

Table 1: Coordinates of the study area (ETRS 3396). Square of 40x40 km.

Easting	Northing
3608062	5932203
3608062	5892203
3648062	5932203
3648062	5892203

Table 2: Overview of available wells in the vicinity of the geothermal study site. ID = Well ID, FT = Formation Thickness, SF = Sandstone Thickness, LFA = lithofacies association (ch-d=distributary channel, cr-d=crevasse splay).

ID	Easting	Northing	FT	SF	LFA
A	3628333	5920342	69	25	ch-d
B	3630527	5927910	50	38	ch-d
C	3630703	5928386	57	29	ch-d
D	3633864	5930872	45	30	ch-d
E	3609678	5924878	70	19	cr-d
F	3631662	5931041	68	19	ch-d
G	3633925	5930289	56	33	ch-d
H	3633833	5930557	70	28	cr-d

3. METHODS

3.1 Subsurface reservoir mapping

The approach and work flow of subsurface reservoir mapping in the North German Basin was explained in detail by Franz et al. (2015, 2018). Following a detailed litho- and biofacies analyses of available outcrops and cored wells, biostratigraphically dated sections are used to reconstruct stratal pattern architectures and to define genetic surfaces (time lines), such as maximum flooding and regression surfaces, along basin axis–basin margin transects. In order to evaluate reservoir qualities, the petrography, diagenesis and hydraulic parameters are investigated employing microscopic methods, geochemistry and laboratory measurements. The results on reservoir qualities are added to a database. To enable the construction of subsurface maps, the results obtained facies analysis of cored and outcrops are calibrated to wireline logs based on typical logs motifs. This knowledge is then applied to a database of several hundred logged wells. The analyses of facies and net-sandstone thickness for each time line resulted in a set of GIS-based subsurface reservoir maps (Zimmermann et al. 2018).

3.2 Monte Carlo Simulation

The Monte Carlo Simulation (MCS) is a statistical modelling approach that seeks to find the stochastic solution of a deterministic model using a set of random numbers of a given probability distribution as input parameters. The modelling approach of the MCS is given by Ofwona (2008) as:

1. Set up a deterministic model $y = f(x_1, x_2, \ldots, x_i)$
2. Create a set of random input parameters that obey a given probability distribution x_{i1}, x_{i2}, …, x_{ij}
3. Calculate the model response and store the result as y_i
4. Repeat steps 2 and 3 for i = 1 to n (where n is the number of Monte Carlo runs)
5. Analyse the result using histograms, summary statistics, confidence intervals etc.

A crucial aspect of MCS is defining the probability distributions of the input parameter. They should reflect the uncertainty of the input parameters in both aspects the geological knowledge (e.g. reservoir extent) and actual scattering (e.g. permeability distribution within the reservoir layer). Common probability distributions are normal, rectangular and triangular. For scattered data, it is also possible to extract the probability density function (PDF) of a given data set (e.g. permeability values). For this study, the deterministic model calculates the flow rate (l/s) and the Productivity Index (PI) in [m^3/(h*MPa)].

3.3 Static Input parameters for the MCS

The mean annual surface temperature in Northern Germany is approximately 9°C (DWD). The salinity of pore fluids in the North German Basin can be approximated by an increase by about 10 g/l per 100 m depth (Wolfgramm et al. 2014).

Table 3: Independent input parameters for MCS of PI and temperature.

Input parameter	Units	Best Guess	Probability Distribution		
			Type	Min	Max
				SD	
well diameter	inch	8.5	constant		
mean aquifer depth	m	2800	triangular	2600	3000
geothermal gradient	K km^{-1}	34	normal	2	
salinity-depth function	g (l × km)$^{-1}$	91	triangular	90	110

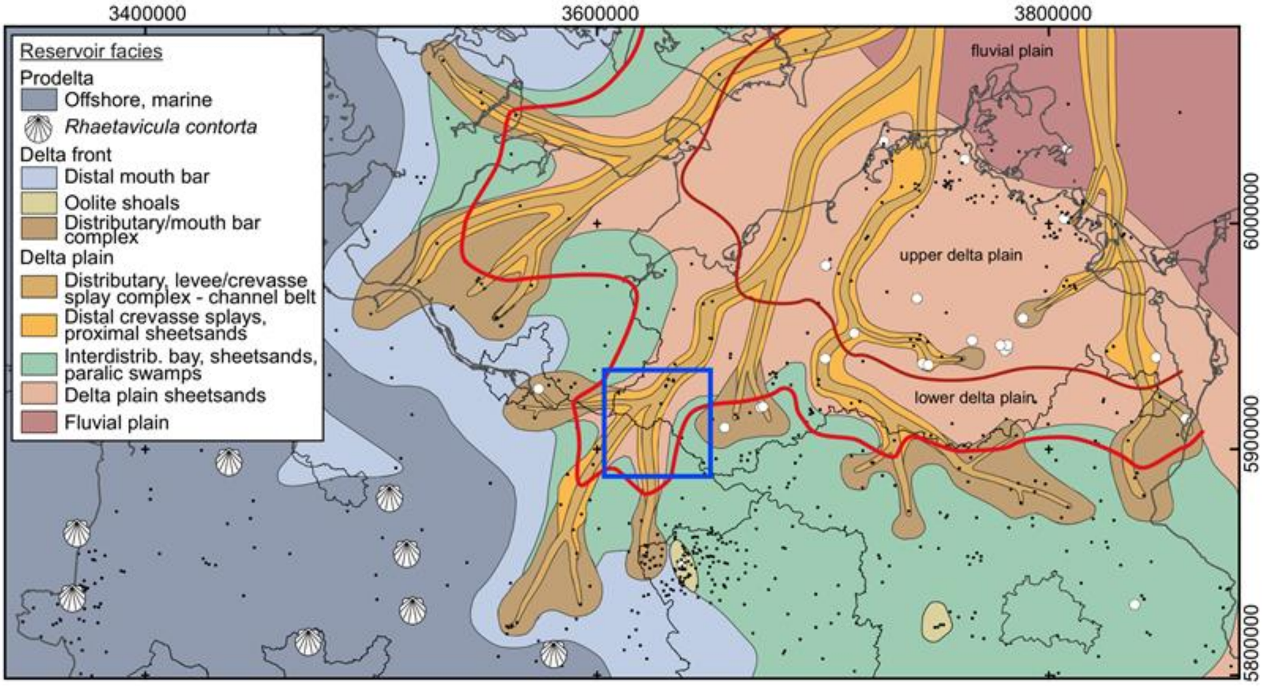

Figure 1: Subsurface map of the Rhaetian deltaic system showing reservoir facies; blue square represents the study area; from Franz et al. (2018).

Several parameters depend linearly on other parameters (e.g. fluid density and viscosity are mainly controlled by the salinity). To calculate the productivity index and the reservoir temperature, independent parameters are given as constraints for the potential site (Table 3).

4. RESULTS

4.1 The Rhaetian deltaic system

The progradation of the Rhaetian elongate high-constructive deltaic system resulted in the deposition of up to 80 m thick delta plain deposits of roughly 47,000 km² in size (Fig. 1). The upper delta plain covers about 26,000 km² and the lower delta plain about 21,000 km², respectively. At the upper and lower delta plain, meandering distributary channels and levee/crevasse splay complexes form channel belt complexes running across the delta plain. In addition, sheetsands and wetland facies associations occur at the upper delta plain and sheetsands, interdistributary bays and distributary/mouth bar complexes occur at the lower delta plain.

At both, the upper and lower delta plain, the channel belts are the most relevant morphological unit for geothermal exploration (Franz et al. 2018). The channel belts are recognised as up to 20 km broad strings in which up to 95 m thick sandstone reservoirs occur (average 45 m, n = 53). These compound reservoirs are due to lateral shifting and avulsion of the distributary channels which resulted in stacking of sandy channel fills, crevasse splays and proximal sheetsands. In the study area, bifurcation of a main distributary running NE-SW formed three individual deltaic lobes (Fig. 1). Based on subsurface reservoir mapping, a hydrothermal reservoir of >30 net-thickness is predicted in the subsurface of the proposed drilling site (Fig. 2).

In the study area, the reservoir temperatures with the median probability are expected to be about 104 °C. Due to the estimated depth of the reservoirs of about 2,800 m (depth error of about 200 m) and the variation of the geothermal gradient (2 K/km standard deviation of the normally distributed geothermal gradient function) it can be assumed that temperatures of more than 100 °C will be achieved with a probability of 75 %. According to reservoir fluid salinity of five neighbouring wells, a salinity of more than 260 g/l will be achieved by 75 % probability. A salinity of more than 280 g/l can be excluded.

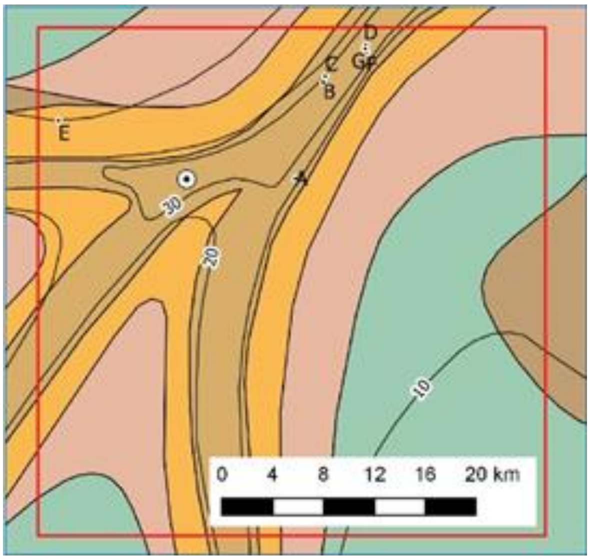

Figure 2: Detail of Fig. 1 showing the study area, net-sandstone thickness and the licence field (red). White dot represents the position of the proposed drilling site.

4.2 Exploration scenario 1: ordinary Kriging

In addition to the fixed parameters, values of net-sandstone thickness and permeability are crucial input parameters to estimate the productivity index for the proposed site. In the neighbouring wells, sandstone thicknesses range from 19 m to 38 m (Table 2). Interpolation by ordinary Kriging gives a reservoir thickness between 22 m and 23 m for the proposed site (Fig. 3). As permeability values of the target reservoir are not available from the neighbouring wells, the mean permeability of 330 mD for the Rhaetian Exter Formation was taken from literature (Wolfgramm et al. 2008). The depth correction resulted in an estimated permeability of 330 mD for the proposed site (Table 3).

Table 4: MCS input parameters to calculate the productivity index of the target reservoir. The permeability was calibrated to reservoir depth of 2,800 m by 20% reduction per 1,000 m (Wolfgramm et. al. 2008, Franz et al. 2018).

Input parameter	Units	Best Guess
net-sandstone thickness	m	23
permeability	mD	330

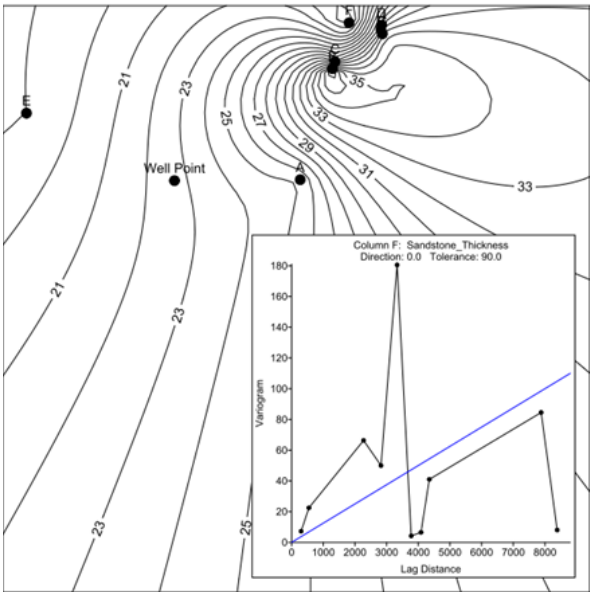

Figure 3: Ordinary Kriging of sand thickness estimation for the proposed geothermal site.

Based on these values, the expected productivity index is calculated to about 40 m³ (h × MPa)$^{-1}$ with a flow rate of about 12 l/s.

4.3 Exploration scenario 2: subsurface reservoir mapping and MCS

For the proposed geothermal site, the aim is to target and develop a hydrothermal reservoir at about 2,800 m depth. The results of subsurface reservoir mapping (Figs. 1, 2) allow setting the probability for each lithofacies association (Tab. 5). With a probability of 55% the drilling will target the channel belt. The probabilities of targeting the channel itself or sheetsands outside the channel belt are 35 % and 10 %, respectively. These are assignments of the probability calculated from the position of the proposed well site with respect to subsurface map which, however, remains a somewhat subjective evaluation.

Subsurface reservoir mapping further allows assigning the net-thicknesses and permeabilities of the target reservoir and their specific probability distribution. In the study area, the mean thickness of distributary channels is assigned to about 30 m (25-35 m), the mean thickness of the channel belt to be about 30 m (20-40 m) and the mean thickness of delta plain sheetsands to be about 10 m (5-15 m). Depth-corrected permeabilities are assigned to be about 400 mD (100-550 mD) for the distributary channel, 350 mD (100-400 mD) for the channel belt and 100 mD (40-150 mD) for delta plain sheetsands (Tab. 5).

The calculation of the productivity index by MCS (2000 runs) resulted in 22 m³ (h × MPa)$^{-1}$ (75% probability) and flow rates of 14 l/s (75% probability).

Table 1. MCS input parameters for MCS of productivity index and temperature.

			Probability Distribution		
Input parameter	Units	Best Guess	Type	Min	Max
				SD	
Probability of lithofacies association:					
channel	%	35	constant		
channel belt complex	%	55	constant		
delta plain sheetsands	%	10	constant		
effective sandstone thickness:					
channel	m	30	triangular	25	35
channel belt complex	m	30	triangular	20	40
delta plain sheetsands	m	10	triangular	5	15
aquifer permeability:					
channel	mD	400	triangular	100	550
channel belt complex	mD	350	triangular	100	400
delta plain sheetsands	mD	100	triangular	40	150

5. DISCUSSION

Although precise reservoir data are very limited in the early stage of geothermal exploration, the demand on reliable prediction of important input data as well as precise risk assessment is high. The classic interpolation of reservoir thickness by ordinary Kriging provide sufficient results, but an equidistant distribution of sandstone thickness is not in agreement with the discrete distribution of sands in recent as well as ancient depositional environments. The previous studies of Franz and Wolfgramm (2008) and Franz et al. (2015, 2018) have shown that sandstone thicknesses within the fluvial-dominated Rhaetian deltaic system do not show an equidistant distribution pattern. Instead, high reservoir thicknesses of > 20 m are closely related to distributary channel belts. For the herein detailed example, calculated sandstone thicknesses vary significantly resulting from the method applied. Ordinary Kriging proposes a sandstone thickness of about 23 m in the subsurface of the proposed well site. In contrast, subsurface reservoir mapping proposes a reservoir thickness of more than 30 m. Sandstone is thickest in areas of distributary channels and decreases with increasing distance from the central channel. Widths of distributary channels and channel belt successions can be calculated by empirical equations from core and well log data (Fielding and Crane 1987, Franz et al. 2018, Zimmermann et al. 2018). Accordingly, the reservoir quality, i.e. high permeability, is closely related to lithofacies associations (Franz et al. 2018).

Although the probability of the expected lithofacies association remains somewhat subjective, the combination of subsurface reservoir mapping with Monte Carlo Simulation provides a more robust assessment of reservoir quality and its probability. By mean of this, a prediction tool may be provided to stakeholders and insurances which delivers probability distributions of expected reservoir parameters, such as productivity index and flow rates.

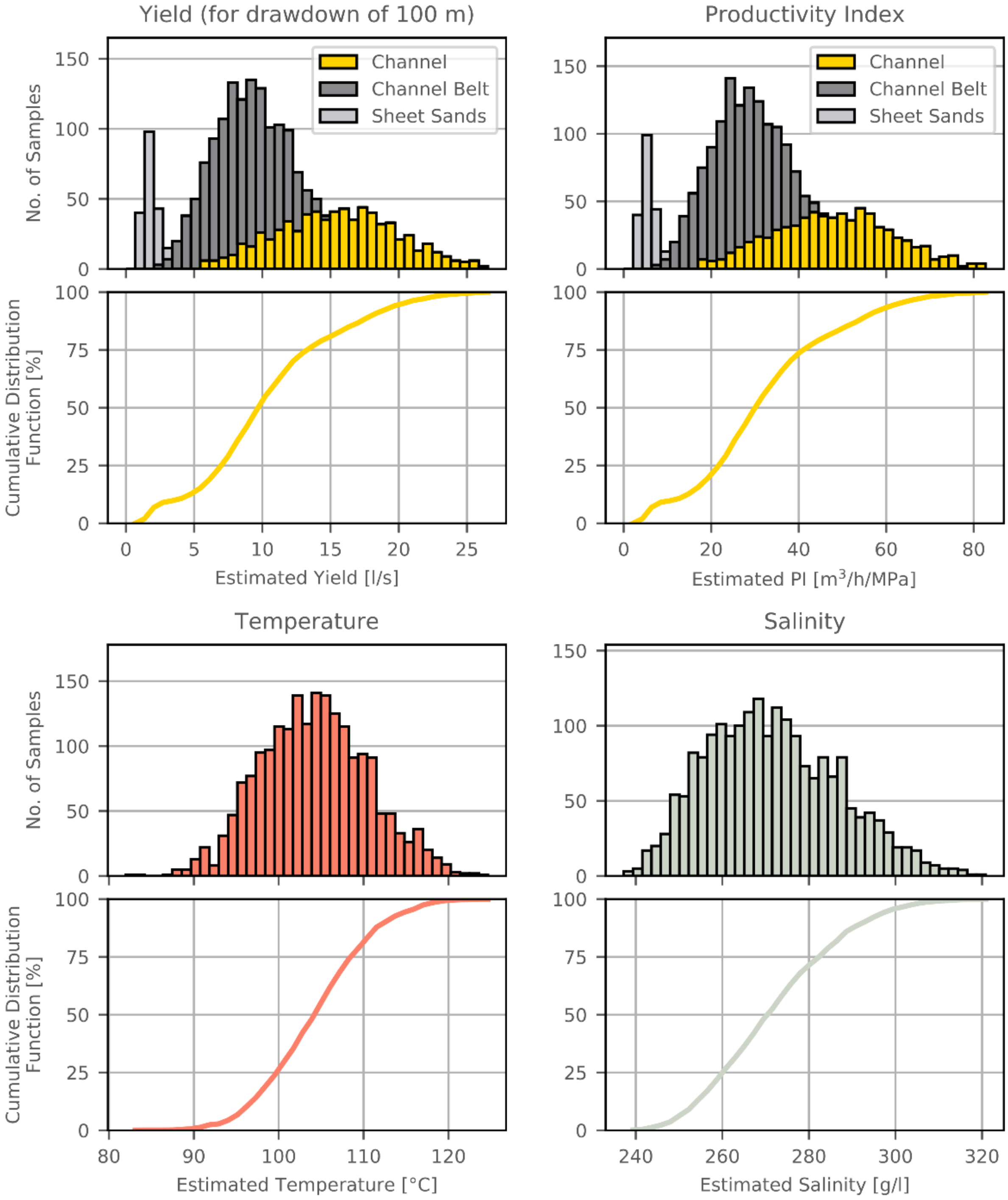

Figure 2: MCS results (2000 runs) for yield, productivity index, temperature and salinity.

6. CONCLUSION

Reservoir prediction and assessment of the exploration risk are integral parts of project developments of geothermal sites. In particular the risk assessment by means of so-called Probability of Success (POS) studies is essential in order to insure stakeholders and financial partner against the geological risk. In the North German Basin, were geothermal exploration focuses mainly on hydrothermal Mesozoic reservoirs (sandstone reservoirs), the geological risk is mainly represented by insufficient reservoir qualities, i.e. low net-thickness and permeability, resulting in low flow rates and productivity indexes. In contrast to POS studies exclusively based on mathematical methods, the herein presented combination of subsurface reservoir mapping and Monte Carlo Simulation (MCS) results in more realistic distribution pattern of reservoir thicknesses and, consequently, enable more reliable risk assessments of flow rates and productivity indexes. -The further integration of reservoir models obtained from subsurface reservoir mapping into POS studies, i.e. by means of weighting factors, will further contribute to meaningful risk assessments of planned geothermal sites.

REFERENCES

Bachmann, G.H. and Grosse, S. (1989) Struktur und Entstehung des Norddeutschen Beckens – geologisch-geophysikalische Interpretation einer verbesserten Bouguer-Schwerekarte. *Niedersächsische Akademie der Geowissenschaften Veröffentlichungen*, 2, 23–47.

Bally, A. and Snelson, S. (1980) Realms of subsidence. In: Miall, A.D. (ed.) Facts and Principles of World Petroleum Occurrence. *Canadian Society of Petroleum Geologist*s, Memoirs, 6, 9–94.

Beutler, G., Röhling, H.G., Schulz, R. and Werner, K.H. (1994) Regionale Untersuchungen von geothermischen Reserven und Ressourcen in Nordwestdeutschland. Endbericht, Archivnr. 111 758, Hannover (*GGA*).

Fielding, C. and Crane, R. (1987) An application of statistical modelling to the prediction of hydrocarbon recovery factors in fluvial reservoir sequences. In: Ethridge, F., Flores, R. & Harvey, M. (eds) Recent Developments in Fluvial Sedimentology. *Society of Economic Paleontologists and Mineralogists*, Special Publications, 39, 321 – 327.

Franz, M. and Wolfgramm, M. (2008) Sedimentologie, Petrologie und Fazies geothermischer Reservoire des Norddeutschen Beckens am Beispiel der Exter-Formation (Oberer Keuper, Rhaetium) NE-Deutschlands. *Zeitschrift für geologische Wissenschaften*, 36, 223 – 248.

Franz, M. Barth, G., Zimmermann, J., Budach, I., Nowak, K. and Wolfgramm, M. (2018) Geothermal resources of the North German Basin: exploration strategy, development examples and remaining opportunities in Mesozoic hydrothermal reservoirs. In Kilhams, B., Kukla, P.A., Mazur, S., McKie, T., Mijnlieff, H.F. and van Ojik, K. (eds) Mesozoic Resource Potential in the Southern Permian Basin. *Geological Society, London*, Special Publications, 469, https: // doi.org / 10.1144 / SP469.11

Franz, M., Wolfgramm, M., Barth, G., Nowak, K., Zimmermann, J., Budach, I. and Thorwart, K. (2015) Verbundprojekt: Identifikation hydraulisch geeigneter Bereiche innerhalb der mesozoischen Sandsteinaquifere in Norddeutschland [R&D project: Hydraulic properties of Mesozoic sandstone aquifers of North Germany]. Forschungsvorhaben, Dokumentation, Schlussbericht *TU Bergakademie Freiberg*, Freiberg, Germany.

Goumas, M.G., Lygerou, V.A. and Papayannakis, L.E. (1999): Computational methods for planning and evaluating geothermal energy projects.- *Energ Policy*, 27, 147-154.

Jung, R., Röhling, S., Ochmann, N., Rogge, S., Schellschmidt,R., Schulz, R. and Thielmann, T. (2002) Abschätzung des Technischen Potenzials der geothermischen Stromerzeugung und der geothermischen Kraft-Wärmekopplung (KWK) in Deutschland. Gutachten im Auftrag des Deutschen Bundestag *Bundesanstalt für Geowissenschaften und Rohstoffe*, Hannover, Germany.

Katzung, G. (ed.) (1984) Geothermie-Atlas der Deutschen Demokratischen Republik. *Zentrales Geologisches Institut*, Berlin.

Lukawski, M.Z., Silverman, R.L. and Tester, J.W. (2016): Uncertainty analysis of geothermal well drilling and completion costs.- *Geothermics*, 64, 382-391.

Ofwona, C. (2008) Geothermal Resource Assessment – Case Example Olkaria I., *United Nations University*, Geothermal Training Programme.

Rockel, W., Hoth, P. and Seibt, P. (1997) Charakteristik und Aufschluss geothermaler Speicher. *Geowissenschaften*, 15, 244–252.

Schulz, R. and Röhling, H.-G. (2000) Geothermische Ressourcen in Nordwestdeutschland. *Zeitschrift für Angewandte Geologie*, 46, 122–129.

Wolfgramm, M., Franz, M. and Agemar, T. (2014) Explorationsstrategie tiefer geothermischer Ressourcen am Beispiel des Norddeutschen Beckens. In Bauer, M., Freeden, W., Jacobi, H., Neu, T. (eds) Handbuch Tiefe Geothermie, *Springer-Verlag*, Berlin Heidelberg.

Wolfgramm, M., Rauppach, K. and Seibt, P. (2008) Reservoir-geological characterization of Mesozoic sandstones in the North German Basin by petrophysical and petrographical data. *Z. geol. Wiss.*, Berlin, 4-5, 249—265.

Ziegler, P.A. (1990) Geological Atlas of Western and Central Europe. Shell Internationale Petroleum Maatschappij, The Hague. *Geological Society*, London.

Zimmermann, J., Franz, M. Schaller, A. and Wolfgramm, M. (2018). The Toarcian – Bajocian deltaic system in the North German Basin: subsurface mapping of ancient deltas – morphology, evolution and controls. *Sedimentology*, 65, 897-930. https: // doi.org / 10.1111 / sed.12410.

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