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Spatial distribution of Mesozoic deposits and their temperature ranges within the Weser-Wiehengebirge Syncline of the inverted Lower Saxony Basin, Minden area, Germany

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Abstract. The provision of climate-neutral, sustainable, and independent heat sources is an essential part of the ongoing transformation of heating systems in Germany. The city of Minden, located at the junction of the river Weser and the Middleland Canal, with its strong industrial sector, faces a massive transition of how heat and energy will be provided for industrial processes as well as heating in the commercial and residential sectors. In our study, we evaluate the structural requirements for the exploitation and utilization of deep geothermal energy from regional Mesozoic rocks, which are known to source thermal springs in the greater Minden area, and geothermal projects in other parts of the North German Basin. The compilation of geological data, seismic data, and rock properties from wells is used to construct a regional structural model as well as temperature distributions based on depth uncertainties of the respective stratigraphic units. Our investigations indicate several stratigraphic units ranging from the Middle Jurassic, Keuper, and Muschelkalk to the Middle Bunter at depths greater than 4100 m below mean sea level with suitable temperatures greater than 150 °C. Seismic data reveal the presence of faults, which may act as a conduit for thermal waters in the northern part of Minden. Our study also provides a basis for further geothermal exploration and exploitation south of Minden, where an operating geothermal system has already been established in the city of Osnabrück and further north, where the potential reservoirs are located at greater depths as shown by hydrocarbon exploration data. First estimations of the geothermal power output for two selected reservoir horizons yield up to 11.3 and 14.3 MW (10 % probability to yield these or higher values), respectively. We conclude that the subsurface of the inverted part of the Lower Saxony Basin principally fulfills the requirements (formation temperatures) for deep geothermal production not only for residential and commercial use but also for industrial processes. However, future detailed reservoir analyses and thermo-hydraulic investigations on a regional scale require additional exploration work like newly acquired seismic surveys and deep exploration wells.

1 Introduction

The provision of climate-neutral, sustainable, and regionally independent sources for industrial and residential heat production is a key to the energy transformation in Germany. One part of the solution for meeting these challenges is extracting heat from subsurface hydrothermal systems. It was proposed that direct use of deep geothermal energy or in combination with large-scale heat pumps is able to compensate partially (up to 25 %) for the total German heat demand. This is complemented with additional heat potential seen for aquifer thermal energy storage systems (ATES) and shal-

low to medium deep geothermal energy (Bracke et al., 2022; Born et al., 2022).

A practical example where an energy transition becomes necessary is the city of Minden, the northernmost city in the state of North Rhine-Westphalia, Germany (Fig. 1). The availability of waterways (Weser River and Middleland Canal) promoted the settlement of numerous industrial branches and businesses within the harbor area to form an extensive industrial park in the northern part of the city outlining the commercial and industrial heat demand. The city of Minden and the larger region around it are already well-known for balneological springs and springs for mineral waters (Fig. 1). The partially Zechstein-salt influenced saline waters are produced from sandstones dated to the Keuper, Muschelkalk, Upper, and Middle Bunter from depths of up to 1000 m (Michel et al., 1998). Future joint utilization of the hydrothermal system requires extensive knowledge about the hydraulic and chemical interactions of the water in the subsurface.

Previous studies in the area around Minden have investigated the subsurface for geothermal energy and other applications. A shallow geothermal project is known from the area of Osnabrück (Fig. 1) where 20 °C warm brine is produced from Muschelkalk carbonates in 360 m depth utilized for a public swimming pool (Michalzik et al., 2012). A deep geothermal project in the wider region of Minden is the GeneSys project with its two major parts "GeneSys Horstberg" (Middle Bunter at depths greater 3600 m and formation temperatures of approximately 150 °C; e.g., Kehrer et al., 2007; Tischner et al., 2010) and "GeneSys Hannover" (Middle Bunter at depths greater 3400 m and formation temperatures of approximately 170 °C; Fig. 1; e.g., Tischner et al., 2010; Hesshaus et al., 2013; Nitschke et al., 2017) initiated by the Federal Institute for Geosciences and Natural Resources (BGR). Other studies in the area of Minden investigated the feasibility of storing CO_2 at depths of 3000 m within the Middle Bunter sandstones (Beni et al., 2012).

In this case study, we evaluate the structural requirements for deep geothermal energy production from regional Mesozoic rocks in the subsurface of the city of Minden. Existing information about the structures of the subsurface (Baldschuhn et al., 2001), currently excluded from the TUNB 3D-model of the North German Basin (BGR, 2022), are integrated with the seismic interpretation of a nearby 2D seismic line (RHBGOSTO U940999) and borehole information from hydrocarbon wells provided by the State Office for Mining, Energy and Geology (LBEG) in Hanover. An analytically derived temperature model provides the first ideas about temperature ranges for the different stratigraphic units. The DoubletCalc software (TNO, 2021) is used to calculate an estimate of the geothermal potential (flow rates, thermal outputs) for selected reservoir horizons.

2 Materials and Methods

2.1 Geological setting and Mesozoic reservoirs

The city of Minden is located in the southernmost part of the inverted Lower Saxony Basin (Fig. 1; Betz et al., 1987; Voigt et al., 2021), a sub-basin of the Central European Basin (Littke et al., 2008). The Weser- and Wiehengebirge Monocline, located to the south of Minden, exposes sub-horizontally, slightly folded Mesozoic and Permian rocks continuing southwest to the edge of the Münsterland Basin (Fig. 2; Deutloff et al., 1982; Geologischer Dienst Nordrhein-Westfalen, 2003). The area between the Weser-Wiehengebirge Monocline is termed Osning Block (Drozdzewski and Dölling, 2018) and covers a strongly faulted and folded Paleozoic basement consisting of Carboniferous and Devonian strata including Lower Carboniferous and Upper/Middle Devonian limestones acting as primary targets for geothermal exploration in most of the remaining part of North Rhine-Westphalia (Arndt, 2021; Balcewicz et al., 2021). The Weser- and Wiehengebirge Syncline follows the monocline to the north before transitioning into the Quetzen Anticline and Schaumburg-Lippe Syncline before faulting within the Rehburg Graben occurs (Fig. 2; Deutloff et al., 1982; Geologischer Dienst Nordrhein-Westfalen, 2003; Drozdzewski and Dölling, 2018). Major faulting in the area of the Weser- and Wiehengebirge Syncline is not evident (Baldschuhn et al., 2001). The river Weser separates the Wesergebirge in the southeast from the Wiehengebirge and their characteristic Kaiser-Wilhelm monument in the northwest.

The stratigraphic column in the area of the city of Minden consists, apart from Quaternary deposits, of Lower Cretaceous rocks exposed within the city limits, Jurassic rocks cropping out along the aforementioned mountain chains and Triassic rocks (Fig. 2; Deutloff et al., 1982). This is equivalent to the North German Basin, another sub-basin of the Central European Basin System (Littke et al., 2008), where several Mesozoic sandstone aquifers have been classified as potential geothermal reservoirs based on their hydraulic properties (porosity/permeability) and thicknesses (Feldrappe et al., 2008; Franz et al., 2018, and references therein). These include the Middle Bunter sandstones of the Solling, Hardegsen, Detfurth, and Volpriehausen formations (e.g., Nitschke et al., 2017; Franz et al., 2018), the Lower to Middle Keuper Stuttgart and Erfurt Formations (e.g., Franz et al., 2015), the Rhaetian sandstones of the Upper Keuper (Franz et al., 2018), Lower and Middle Jurassic sandstones (e.g., Franz et al., 2015, 2018; Kunkel and Agemar, 2019) as well as Lower Cretaceous sandstones (Feldrappe et al., 2008; Franz et al., 2018). Deeper non-hydrocarbon-bearing carbonate reservoirs, such as the Muschelkalk carbonates, have not been a primary exploration target for geothermal energy yet as data is not as abundant as for the hydrocarbon-bearing sandstones. The presence and depth of the Kohlenkalk and Massenkalk carbonates (Arndt, 2021;
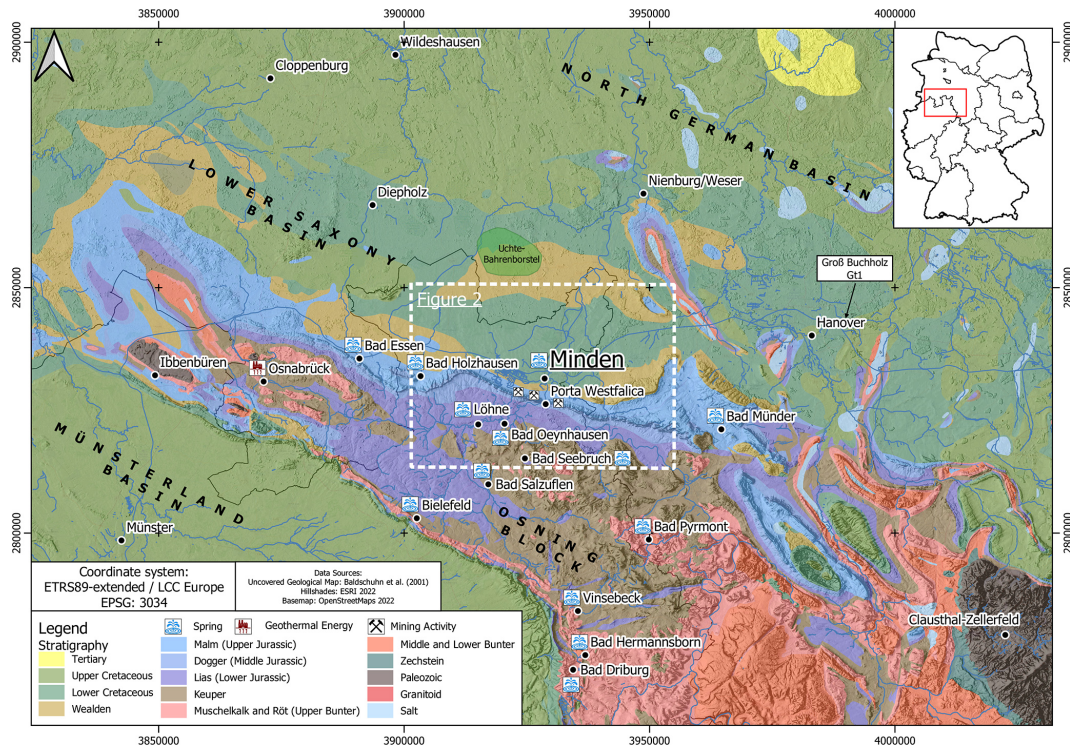
Figure 1. Uncovered geological overview map of the southern margin of the Central European Basin (Baldschuhn et al., 2001; Littke et al., 2008). Springs in several cities on the Osning Block are indicated (Michel et al., 1998). Mining locations in the city of Minden are indicated (Deutloff et al., 1982).

Balcewicz et al., 2021) remains unknown as data is only available to the Upper Carboniferous in the southern part of the Lower Saxony Basin.

## 2.2 Geological, regional and structural map data

In addition to the structural maps of the Geotectonic Atlas of Northwest Germany (Baldschuhn et al., 2001), a geological map of Minden (Deutloff et al., 1982) provides valuable input data for the structural modeling of the area between the Weser-Wiehengebirge Monocline and the Quetzen Anticline. The structural maps are available for several stratigraphic units (scale 1 : 300 000) and are georeferenced. Isolines with a spatial density of 100 m, representing the common depth of a stratigraphic unit at a certain location, were digitized as LineStrings at regular intervals using the QGIS geographic information system (QGIS Development Team, 2022). The structural model was then created based on the digitized data. The recently published TUNB 3D-model of the North German Basin (BGR, 2022), which is also based on the data compiled by Baldschuhn et al. (2001), seismic data sets and well data, does not cover the area of Minden (https://gst.bgr.de/, last access: 10 January 2023).

Zonal statistics of the rasterstats Python package (Perry, 2021) considering the city limits of Minden were used to derive the minimum (edge of the syncline), median and max-

imum (center of the syncline) depths z of the geological structures for subsequent temperature calculations. An uncertainty for the minimum, median, and maximum depths of each stratigraphic unit is derived from an estimated depth-dependent standard deviation of a normal distribution according to Eq. (1). This uncertainty is defined as there are no deeper wells or depth-converted seismic data available for this study in the immediate vicinity of Minden. Rabbel et al. (2017) also report depth uncertainties with respect to a seismic velocity model misplacing the target horizons by up to 300 m where target depths are lower than in our case. It is therefore assumed that there is a depth uncertainty $\sigma_z = \pm 10\%$ for the first 1000 m of the resulting structural model which increases linearly with depth by 1 % per 1000 m. At a depth of 2000 m, the depth uncertainty would be $\pm 11\%$, at 3000 m it would be $\pm 12\%$ and so on. This depth uncertainty is seen as plausible as recent drilling results for geothermal wells in the North German Basin (Hamburg-Wilhelmsburg) encountered such deviations from the original well prognosis (reported at the 13. Norddeutsche Geothermietagung – 12 May 2022; Sävecke, 2022).

Random values of minimum, median and maximum depths were drawn from the normal distribution with the associated depth distribution. Geothermal gradients drawn from a second normal distribution were then multiplied with the randomly drawn depths to obtain a final temperature dis-
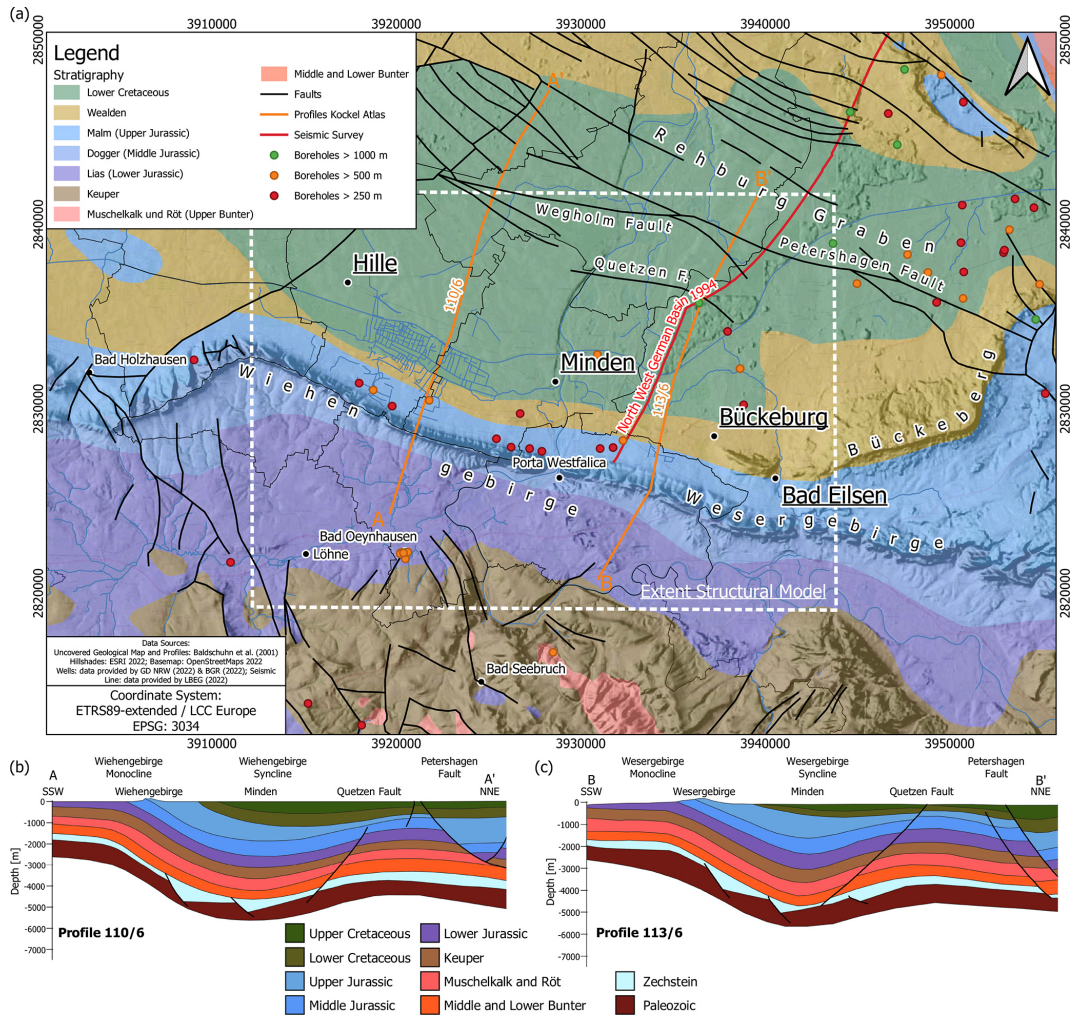
Figure 2. (a) Uncovered geological map of the area of Minden zoomed in from Fig. 1 (Baldschuhn et al., 2001). The locations of the cross-section in **(b)** and **(c)** and the integrated seismic section (RHBGOSTO U940999) are indicated. Wells with a depth greater than 250 m are shown. **(b)** & **(c)** Profiles 110/6 and 113/6 across the Wiehengebirge and Wesergebirge Monocline and Syncline (Baldschuhn et al., 2001).

tribution T in the subsurface for each stratigraphic unit according to Eq. (2). The average geothermal gradient of the Minden area was set to $\frac{dT}{dz} = 34.1\,°\text{C}\,\text{km}^{-1}$ with a standard deviation of 2.5 °C according to data from GeotIS (Agemar et al., 2012). P10, P50 (median), P90 temperatures in addition to Q1, Q3, minimum and maximum temperatures for boxplots will be reported to describe the temperature ranges.

$$\sigma_z = \begin{cases} 0.1 \cdot z \\ \quad \text{if } z <= 1000\,\text{m b.s.l.} \\ 0.1 \cdot z + (z - 1000\,\text{m}) \cdot z \times 10^{-5} \\ \quad \text{if } z > 1000\,\text{m b.s.l.} \end{cases} \tag{1}$$

$$T = z \cdot \frac{dT}{dz} \tag{2}$$

2.3 Borehole data

Borehole data are available for North Rhine-Westphalia (NRW) and Lower Saxony provided by the Geological Survey NRW (GD NRW) and the LBEG, respectively. Lithostratigraphic logs are mostly available for boreholes in NRW, while geophysical logs from the nearby Uchte and Bahrenborstel gas fields were used for comparison and further investigations (Fig. 3). Only two of the twelve provided borehole data sets including logs were usable. The depths of displayed boreholes range from 250 m to more than 3500 m (Fig. 2). The logs and their data were split according to the reported stratigraphic classifications. Average values from these data ranges were now taken for further investigations.

2.4 2D seismic data

The 2D profile RHBGOSTO U940999 of the "North-West German Basin 1994" survey (Fig. 2) acquired by what is today the ExxonMobil Production Deutschland GmbH was provided by the LBEG in the time domain. A structural and stratigraphic interpretation was performed along the line covering the synclinal structure of Minden and partly the Quetzen Anticline. A seismo-stratigraphic framework was developed after Ahlrichs et al. (2020) compiling lithologies and seismic facies including amplitude, frequency, continuity, bounding relationships, reflector characteristics, and a seismic section example. The framework consists of seismic units representing a mappable interval of seismic reflectors (Ahlrichs et al., 2020). Boundaries of seismic units are identified and classified by marker reflections, unconformities, or correlative conformities (Ahlrichs et al., 2020). A total of eight seismic units (H1 to H8) excluding the basement were defined. A regional velocity model is not available to perform a time-depth conversion. Well markers from deeper wells nearby (e.g. Quetzen 1, drilled 1955, 1077 m deep) could not be converted to a well-to-seismic-tie due to imaging quality around the well and lack of a well path and since no check shots or vertical seismic profilings are available. The depths of tops of seismic units were hence expressed in two-way-travel time (TWT) and converted into thicknesses of seismic units using average velocities from the received borehole data. The depths resulting from stacked unit thicknesses were compared to those of the Geotectonic Atlas (Baldschuhn et al., 2001).

2.5 Geothermal Potential Calculations using DoubletCalc

The geothermal potential expressed as possible flow rates ($m^3 h^{-1}$), coefficient of performance (COP, $kW kW^{-1}$), and thermal power outputs (MW) is calculated using the DoubletCalc software developed and maintained by TNO (2021). Aquifer properties, doublet and pump properties, and well properties can be defined to estimate the geothermal power of a geothermal doublet. The software uses a Monte-Carlo approach based on provided min-median-max ranges of the aquifer properties and a depth uncertainty of the reservoir of $\pm 10\%$ (TNO, 2021). DoubletCalc is applied to the Schilfsandstein (Keuper) and the Detfurth Sandstone (Middle Bunter). The parametrization is provided in Table 1.

3 Results

3.1 Structural model and temperature at depth

The constructed structural geological model indicates the depths of the potential reservoir units within the Weser-Wiehengebirge Syncline in the area of Minden. Seven stratigraphic boundaries ranging from the base of the Lower Cretaceous to the base of the Bunter were constructed. The depth of the modeled units, including the potential geothermal reservoirs, vary from 250 ± 23 m TVDSS (true vertical depth sub-sea) for the Base Lower Cretaceous – Top Wealden/-Top Upper Jurassic at the edge of syncline to 4981 ± 696 m TVDSS for the Base Lower Bunter – Top Zechstein in the center of the syncline (Table 2). The structural model also depicts the Weser-Wiehengebirge Syncline with the highest depths for the Top Middle Bunter and the overlying stratigraphic units in a stretch from the village of Hille in the west through the city center of Minden and to the northern part of the city of Bückeburg and Bad Eilsen in the east (Fig. 4). This corresponds to a 30 km long NWW-SEE trending structure with depths greater 3000 m. To the south, the model becomes shallower with depths for the Top Middle Bunter of around 800 m TVDSS (Fig. 4). The northern part of the model including the Quetzen Anticline reaches depths of less than 2700 m TVDSS (Fig. 4). Larger faults and associated offsets of approximately up to 100 m are only indicated for the area of Bad Oeynhausen. One fault at the northern margin of the syncline, here termed Quetzen Fault, indicates an offset of 10s of meters (Fig. 4).

The corresponding analytically calculated median temperatures for the Top Middle Bunter, the stratigraphic unit holding the deepest reservoir units, range between 85 °C for the shallowest depth (2143 ± 239 m) in the marginal area and 151 °C for the greatest depth (4103 ± 538 m) for the center of the syncline (Fig. 4). The P90 temperatures for all stratigraphic units range between 19 and 148 °C while the P50 temperatures range between 20 and 181 °C and the P10 temperatures range between 22 and 216 °C (Table 2 and Fig. 5). The values indicate an increase in temperature with depth but also a larger variation of temperatures due to the increase of uncertainty with depth (Fig. 5).

3.2 Seismic interpretation and borehole data

Interpreting horizons H1 to H8 (from bottom to top) on seismic line RHBGOSTO U940999 was enabled based on the strong impedance contrasts in the subsurface (Fig. 6 and Tables 3, 4 and 5). Some of the stratigraphic boundaries are indicated by truncations and onlaps. Due to the absence of well-ties in the immediate vicinity of Minden, the depth conversion approximated by using the mean values of P-velocities from the well log of Uchte T9 ($4500 m s^{-1}$) serves as a comparison to the structural geological model (Baldschuhn et al., 2001).

Table 3 outlines the maximum depths of the respective stratigraphic boundaries in milliseconds and converted to depth as well as the thickness of the stratigraphic units in milliseconds and meters for the southwestern and northeastern margin of the syncline. Tables 4 and 5 provide a seismo-stratigraphic concept for this study after Ahlrichs et al. (2020) summarizing the nomenclature for seismic reflectors, the respective seismic units, the lithology accord-
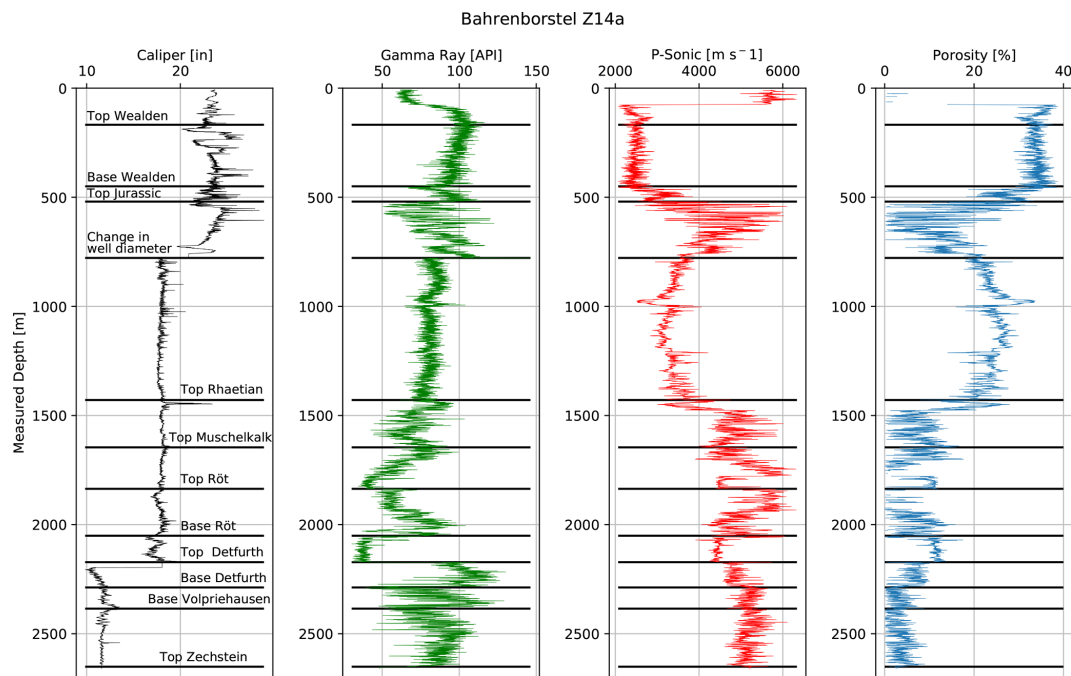
Figure 3. Well logs for the well Bahrenborstel Z14a, one of the usable data sets provided by LBEG in 2022. Negative porosities were omitted. Reservoir parameters were obtained from these logs. Stratigraphic boundaries were extracted from publicly available data of the well Bahrenborstel Z14.

Table 1. DoubletCalc parametrization for the Keuper and Middle Bunter sandstones.

Aquifer Properties	Value (Keuper/Middle Bunter)			Unit	Source (Keuper/Middle Bunter)
	min	median	max		
Aquifer permeability	13/13	1302/577	4659/1000	md	Franz et al. (2015)/Putnis and Mauthe (2001), May et al. (2004), Tischner and Hesshaus (2015)
Aquifer net to gross	0.2	0.5	1	–	Assumption
Aquifer gross thickness	5/5	20/22	35/39	m	Franz et al. (2015)/May et al. (2004), Uchte Z3
Aquifer top at producer	2733/3693	3037/4103	3341/4513	m	This study
Aquifer top at injector	2733/3693	3037/4103	3341/4513	m	This study
Aquifer water salinity	175 000	250 000	325 000	ppm	Franz et al. (2018)
Aquifer kh/kv ratio		1		–	Assumption
Surface temperature		10.4		°C	Deutscher Wetterdienst
Geothermal gradient		0.0341		°C m^{-1}	Agemar et al. (2014)
Doublet and Pump Properties		Value		Unit	Source
Exit temperature at heat exchanger		40/60		°C	Assumption
Distance wells at aquifer		1100		m	Assumption
Pump system effiency		0.68		–	Assumption
Production pump depth		500/700		m	Assumption
Pump pressure difference		40		bar	Assumption
Well Properties		Value		Unit	Source
Outer diameter producer/injector		8.5		inch	Assumption
Skin producer/injector		0.2		–	Assumption
Penetration angle producer/injector		0		°	Assumption
Pipe inner diameter in reservoir		8.5		inch	Assumption
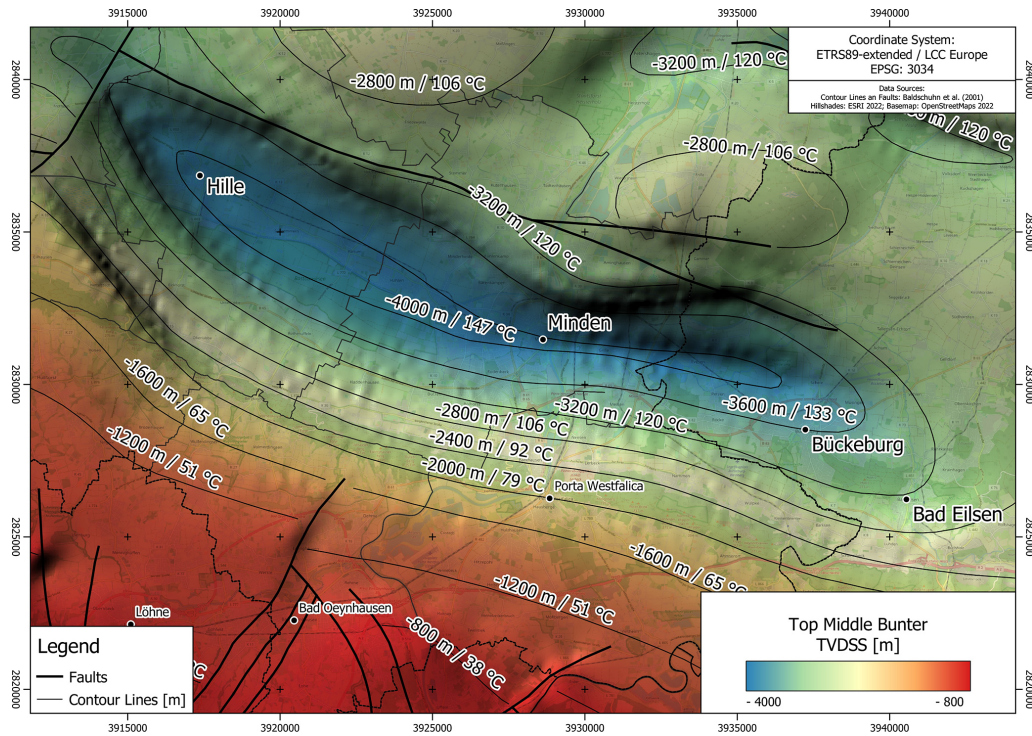
Figure 4. Structural model for the top of the Middle Bunter. The structure of the Weser-Wiehengebirge Syncline is clearly visible. Depths of isolines and associated temperatures according to the average geothermal gradient of $\frac{\mathrm{d}T}{\mathrm{d}z} = 34.1\,°\mathrm{C\,km^{-1}}$ (Agemar et al., 2014).
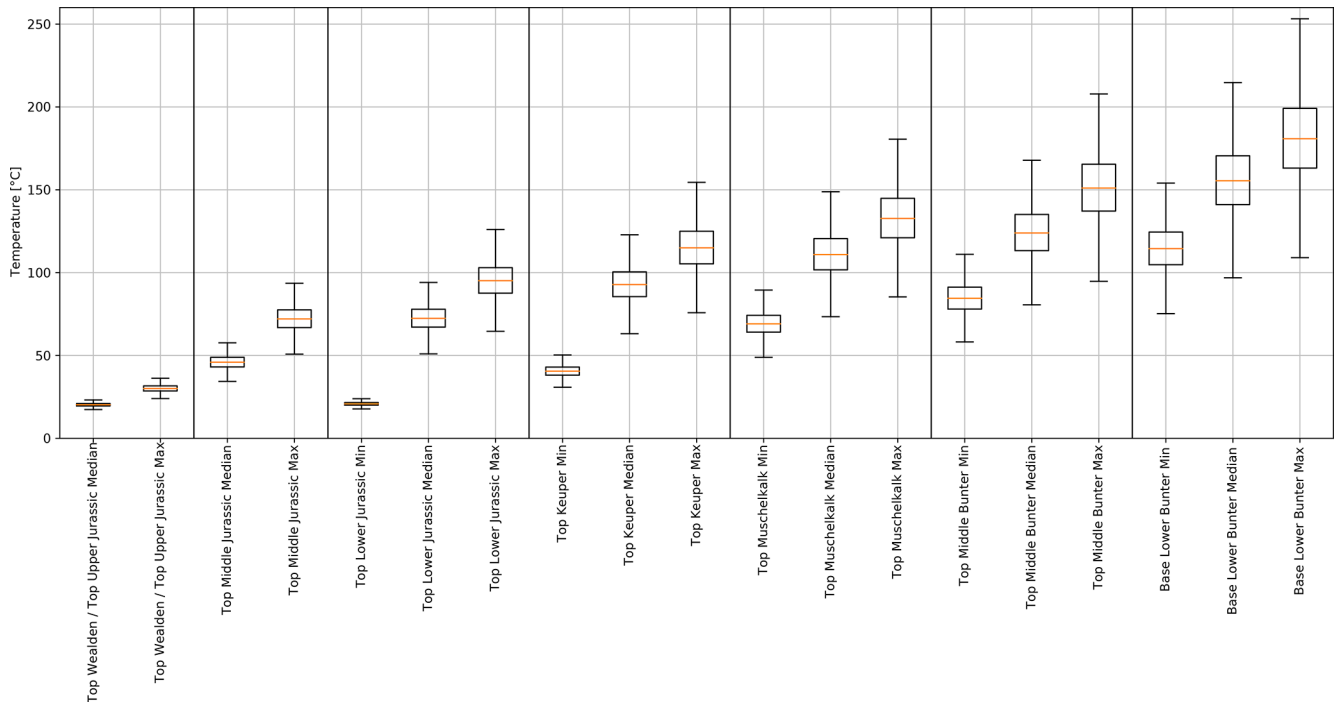
Figure 5. Boxplots showing the temperature distributions for the different tops and base (Lower Bunter) of the different stratigraphic units. Minimum, where available, median and maximum temperature scenarios are given for each stratigraphic unit. The temperature ranges are a function of the depth uncertainty of each scenario.

Table 2. Depths and temperature ranges for the tops and the base (Lower Bunter) of the different stratigraphic units of the structural model. P10, P50, and P90 as well as temperatures of Fig. 5 are shown (TVDSS = true vertical depth sub-sea). NA = invalid temperatures below the surface temperature of 10.4 °C.

Stratigraphic Unit	Location	Depth TVDSS (m)	Geothermal Gradient (°C km^{-1})	Temperature P90 (°C)	Temperature P50/Median (°C)	Temperature P10 (°C)	Temperature Q1 (°C)	Temperature Q3 (°C)	Temperature Min (°C)	Temperature Max (°C)
Top Wealden/	Min Depth	NA		NA	NA	NA	NA	NA	NA	NA
Top Upper	Median Depth	250 ± 23		19	20	22	19	21	17	23
Jurassic	Max Depth	540 ± 52		27	30	33	28	31	24	36
Top Middle	Min Depth	NA		NA	NA	NA	NA	NA	NA	NA
Jurassic	Median Depth	1007 ± 101		41	45	52	43	48	34	57
	Max Depth	1777 ± 191		62	72	83	66	77	50	93
Top Lower	Min Depth	267 ± 25		19	21	22	20	21	17	23
Jurassic	Median Depth	1787 ± 192		63	72	83	67	77	50	94
	Max Depth	2456 ± 281		81	95	110	87	103	64	126
Top Keuper	Min Depth	847 ± 83	34.1 ± 2.5	36	41	45	38	43	30	50
	Median Depth	2389 ± 272		79	93	108	85	100	63	122
	Max Depth	3037 ± 366		97	115	134	105	125	75	154
Top Muschelkalk/	Min Depth	1688 ± 180		60	69	79	64	74	48	89
Upper Bunter	Median Depth	2923 ± 348		94	111	130	101	120	73	148
	Max Depth	3563 ± 448		111	133	156	121	144	85	180
Top Middle	Min Depth	2143 ± 239		72	85	98	78	91	58	111
Bunter	Median Depth	3307 ± 407		104	124	146	113	135	80	167
	Max Depth	4103 ± 538		125	151	179	137	165	94	207
Base Lower	Min Depth	3027 ± 364		96	114	134	104	124	75	154
Bunter	Median Depth	4237 ± 561		128	155	184	141	170	96	214
	Max Depth	4981 ± 696		148	181	216	163	199	109	253

ing to Deutloff et al. (1982), the characteristics for amplitude, frequency, continuity, bounding relationships and further seismic characteristics including a sample seismic section.

3.3 Geothermal Potential

The stochastic simulations using DoubletCalc resulted in probability distributions (P10, P50, P90) for the expected pump volume flow, the coefficient of performance, and the geothermal power (Fig. 7). The calculated pump volume flows range from 30.8 m^3 h^{-1} (P90 Middle Bunter) to 194.2 m^3 h^{-1} (P10 Keuper). The pump volume flow is generally higher for the Keuper sandstone compared to the Middle Bunter sandstone since permeabilities are lower in the deeper reservoir. The COP ranges from 36.0 kW kW^{-1} (P90 Keuper) to 52.8 kW kW^{-1} (P10 Middle Bunter). The resulting geothermal power ranges from 1.8 MW (P90 Middle Bunter) to 14.3 MW (P10 Keuper).

4 Discussion

4.1 Analytically derived depths and temperatures

The results of the determined minimum, median and maximum depths as well as associated analytically calculated temperatures derived from a geothermal gradient of 34.1 ± 2.5 °C provide a first model-driven temperature estimation of the subsurface and in particular for the strati-graphic units hosting the potential geothermal reservoirs (Table 2; Agemar et al., 2012). At the time of its creation during the late 20th century, the authors of the Geotectonic Atlas integrated all data (seismic data, well data, surface information) and knowledge available to the federal authorities at that time (Baldschuhn et al., 2001). Regional velocity models, check-shots, and well-ties were used to convert acquired seismic two-way-travel-time data to depth. These efforts resulted in a comprehensive atlas outlining the structures in the center of the North German Basin but also at its margins where geophysical data or well data is not as abundant as in the areas of former or current hydrocarbon exploration. The median temperature and depths for the respective stratigraphic units (Table 2) indicate that Cretaceous to Middle Jurassic units, if present in a porous and permeable facies, may only be used for medium-deep geothermal applications with depths of approximately 1000 m and temperatures of 45 °C. Reservoirs of the Keuper, Muschelkalk, if present in a porous and permeable facies, excluding the Upper Bunter reach median temperatures of up to 111 °C and median depths of approximately 3000 m and may therefore be used directly or in combination with heat pumps for domestic and commercial purposes. Median temperatures of approximately 125 °C for the Middle Bunter may not only be suitable for domestic and commercial purposes but also for industrial applications. However, P90 temperatures of 72 °C (min depth), median temperatures of 124 °C (median depth) and P10 temperatures of 179 °C (max depth) outline the current uncertainties associated with the depth and temperature

Table 3. Compilation of results of the seismic interpretation. The table shows the depth and thicknesses of the different stratigraphic units in milliseconds and converted to meters.

| Stratigraphic units | Deepest point (syncline) | | | Thickness | | | |
| | | | | SW | | NE | |
	time (ms)	depth-converted (m)	trace	time (ms)	depth-converted (m)	time (ms)	depth-converted (m)
Lower Cretaceous	380	855	185	Max. thickness of 380 ms (855 m) with decreasing trend to the edges			
Base Malm/Top Dogger	690	1552	182	334	751	120	270
Base Dogger/Top Lias	1071	2410	166	299	673	207	466
Base Lias/Top Keuper	1292	2907	150	218	490	154	346
Base Keuper/Top Muschelkalk	1607	3616	140	422	949	315	709
Base Muschelkalk/Top Bunter	1745	4136	140	161	362	172	387
Base Bunter/Top Zechstein	1969	4430	160	186	418.5	397	893
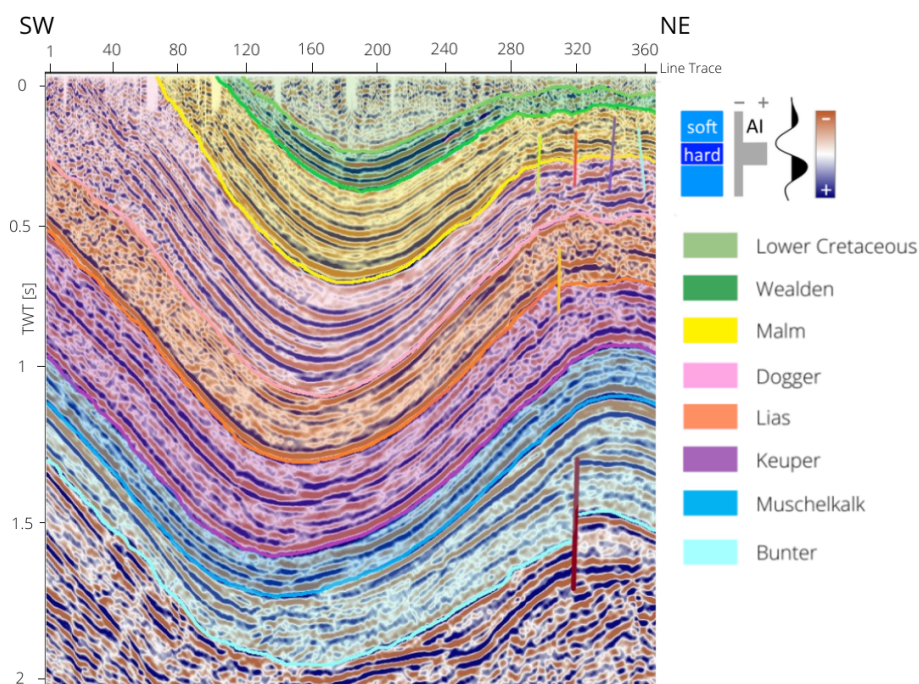
Figure 6. Interpreted seismic section RHBGOSTO U940999 displaying the Mesozoic stratigraphic units of the Weser-Wiehengebirge-Syncline (SW) and adjacent Quetzen Anticline (NE).

of the reservoirs and stress the need for tighter integration of newly acquired data and petrophysical data to reduce these ranges for a better subsurface temperature prediction.

The stochastic simulations for the geothermal potential of the Keuper and Middle Bunter reservoirs show a range of expected flow rates, COPs, and geothermal power erstimates. The higher temperature in the Middle Bunter reservoir cannot compensate for the higher flow rates for the Keuper reservoir. Therefore, the geothermal power is higher for the shallower, colder but more permeable Keuper reservoir.

4.2 Geological and geophysical interpretations

The structural and stratigraphic investigations of the 2D seismic profile RHBGOSTO U940999 (Fig. 6 and Tables 4, 5) according to the concept of Ahlrichs et al. (2020) allowed for the interpretation of eight major seismic units within the Weser-Wiehengebirge Syncline and Quetzen Anticline above Permian Zechstein evaporites. Seismic characteristics of these units allowed for a correlation to stratigraphic units (Bunter to Lower Cretaceous from bottom to top) in accordance with the local stratigraphy (Deutloff et al., 1982) and the existing structural model after Baldschuhn et al. (2001).
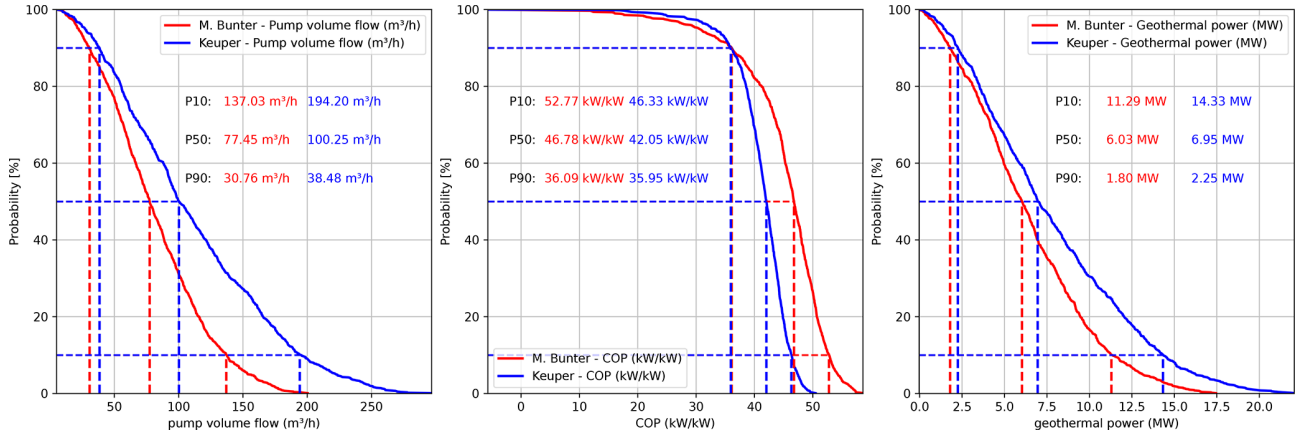
Table 4. See Table 5.

Figure 7. Stochastic simulations of pump volume flow, coefficient of performance, and geothermal power for the Keuper and Middle Bunter sandstones.

Displacements along faults of several hundreds of meters as described by Baldschuhn et al. (2001) are not evident from seismic interpretations. The available seismic section RHB-GOSTO U940999 shows relatively minor fault offsets at shallow depths within a mostly folded but hardly faulted area. This implies that, in contrast to fluid pathways described by Michel et al. (1998) for the thermal springs south of Minden, a fault-related ascend of thermal waters is less likely in the subsurface of Minden due to the lack of larger faults. Pro-

duction from non-faulted sandstone reservoirs may therefore result in lower production rates.

A simplified depth conversion integrating mean seismic P-wave velocities showed results with large deviations from the horizons mapped by Baldschuhn et al. (2001) ranging for all stratigraphic units between -543 m (Base Lower Cretaceous) and 267 m (Base Lower Bunter, Table 6). A negative difference indicates an overestimation of the seismic velocities whereas a positive difference an underestimation of the

Table 5. Continuation of Table 4. Seismo-stratigraphic concept for this study after Ahlrichs et al. (2020). The table summarizes the nomenclature for seismic reflectors, the respective seismic units, the lithology according to Deutloff et al. (1982), the characteristics for amplitude, frequency, continuity, bounding relationships and further seismic characteristics including a sample seismic section. The size of individual series do not scale to the true timespan.

Era	Period	Series	Group	Subgroup	Stage (Menning, 2018)	Formation (Deutloff & Skupin, 1982; GD NRW 2022)	Reflectors	Seismic Unit	Lithology (Deutloff & Skupin, 1982)	Amplitude	Frequency	Continuity	Bounding relationship (to layer below)	Characteristics	Seismic Examples
Mesozoic	Triassic	Upper	Keuper	Upper	Rhaetian	Rhaetian	H3	Keuper	Claystones, Siltstones, Sandstones, Marls, Dolostones, Gypsum	moderate (central part), low (margins)	low	moderate	Mostly concordant	disturbed (NE, SW margins), retrograding clinoforms	
				Middle	Norian	Steinmergelkeuper (Arnstadt) Weser Layers (Rote Wand) Stuttgart Layers (Schilfsandstein) Gipskeuper									
					Carnian										
				Lower	Ladinian	Erfurt Layers (Lettenkohlenkeuper)									
		Middle	Muschelkalk	Upper		Ceratiten-Layers Trochitenkalk Warburg Layers	H2	Muschelkalk	Limestones, Marls, Dolostones, Gypsum, Anhydrite, Halite	moderate (central part), low (margins)	moderate	moderate	Mostly concordant	subparallel	
				Middle	Anisian	Karlstadt to Diemel Layers									
				Lower		Wellenkalk									
		Lower	Buntsandstein	Upper		Röt	H1	Bunter Sandstone	Sandstones, Siltstones, Claystones, Gypsum, Halite	low, higher at top	moderate	low (bottom), moderate (top)	Discordant to Permian evaporitic deposits	subparallel (top)	
				Middle	Olenekian	Solling Detfurth Volpriehausen									
				Lower	Induan	Bernburg Calvörde									
Paleozoic	Permian	Lopingian	Zechstein		Changhsingian	Zechstein Sequence	B	Basement	Siliziclastic, calcerous, evaporitic rocks	low to high	moderate	low to high		Zechstein: transparent Rotliegend: strong reflections Carboniferous: chaotic	
					Wuchiapingian										
		Guadalupi	Rotliegend		Capitanian	Rotliegend Sequence									
					Wordian										
					Roadian										
		Cisuralian			Kungurian										
					Artinskian										
					Sakmarian										
					Asselian										
	Carboniferous	Pennsylv.	Silesian		Stefanian	Hiatus									
					Westfalian	Coal-bearing strata									
					Namurian	Non-coal-bearing strata									
		Mississipp.	Dinantian		Visean	Dinantian Carbonates (Kohlenkalk Group)									
					Tournaisian										

seismic velocities. This is evident from well logs (Fig. 3) showing seismic velocities of approximately 2500 m s^{-1} for the Lower Cretaceous and Wealden increasing to approximately 3250 m s^{-1} for the Jurassic before reaching seismic velocities of 4500 m s^{-1} and higher in Triassic units. A better understanding of the seismic velocities in the subsurface of Minden is hence necessary to properly position the stratigraphic units at depth.

Therefore, a depth uncertainty between 10 % and 15 % between the structural model and the seismic data is seen as reasonable for the sparse distribution of subsurface data. These uncertainties in depth are of the same magnitude as encountered in recently drilled geothermal wells in the North German Basin (Hamburg-Wilhelmsburg, variations in depths between the original well prognosis and the actual drilling results, reported at the 13. Norddeutsche Geothermietagung – 12 May 2022; Sävecke, 2022).

The key results of this study indicate that potential reservoirs or at least their associated stratigraphic intervals are mapped in the subsurface of Minden using the provided 2D seismic data. This reduces the risk for the regions further to the southwest such as Bad Oeynhausen or Bielefeld where stratigraphic units down to the Bunter or even Carboniferous

have been intersected by wells before as a continuation of the layers in the subsurface can be assumed. The seismic survey may further act as a starting point for exploration campaigns to come.

However, the true depths and thus formation temperatures of the reservoirs, their thicknesses of the net aquifers, internal structures, diagenetic history, and internal facies distributions remain uncertain. Hence, an exploration well in the Minden area would not only reduce the uncertainty and de-risk the prospect with respect to the presence, depth and temperature of the reservoir rocks but also the uncertainty associated with facies distributions, diagenetic history and petrophysical properties. These new results could then be compared to the existing wells in the Uchte/Bahrenborstel area or the area south of Minden. All obtained results could be integrated into a more comprehensive numerical reservoir model to determine possible flow rates thermal outputs of the respective reservoirs. The consideration of seismic data and structural data promotes the exploration for geothermal energy not only below the city of Minden but also along the entire 30 km long NWW-SEE trending Weser-Wiehengebirge Syncline. With depths greater than 3000 m also in the area of Hille to the west and Bückeberg to the east, the Mesozoic stratigraphic

Table 6. Comparison between the depth converted stratigraphic boundaries of seismic line RHBGOSTO U940999 and the constructed structural geological model (TVDSS = true vertical depth sub-sea). A negative difference indicates an overestimation of the seismic velocities whereas a positive difference indicates an underestimation of the seismic velocities.

Stratigraphic Unit	TVDSS (Seismic) (m)	TVDSS (Structural Model) (m)	Difference (m)
Base Lower Cretaceous/ Top Upper Jurassic	855	312	−543
Base Upper Jurassic/ Top Middle Jurassic	1552	1333	−219
Base Middle Jurassic/ Top Lower Jurassic	2410	2211	−199
Base Lower Jurassic/ Top Keuper	2907	2869	−38
Base Keuper/ Top Muschelkalk	3616	3445	−171
Base Muschelkalk/ Top Upper Bunter	4136	4053	−83
Base Lower Bunter/ Top Zechstein	4430	4697	267

units could also be investigated for their geothermal potential in these regions.

5 Conclusions

In this study, we have compiled surface and subsurface data from the area of Minden in the inverted part of the Lower Saxony Basin, northwestern Germany. The aim of our study was to create a structural geological model of the subsurface, to interpret a local seismic survey to identify seismic units and stratigraphic units which include siliciclastic and calcareous reservoir units already known and utilized in the larger North German Basin area and to calculate a first temperature distribution integrating associated depth uncertainties of the structural model. The first estimation of flow rates, coefficient of power, and thermal power outputs completes a first investigation of the geothermal potential.

The key results of our investigation indicate the following:

– The presence of several stratigraphic units within the inverted Lower Saxony Basin in the city of Minden as already postulated by Baldschuhn et al. (2001) ranging from the Upper Jurassic, Keuper, Muschelkalk and Middle Bunter down to depths greater 4100 m TVDSS that may contain geothermal reservoir units such as sandstones but also carbonates is confirmed by interpreting a previously unpublished 2D seismic line.

– The stratigraphic units hosting potential geothermal reservoirs could be identified on seismic line RHBGOSTO U940999 and thus their presence could be proven in the immediate vicinity of Minden using a seismo-stratigraphic concept.

– The seismic line and the constructed structural geological model further outline the structure of the Weser-Wiehengebirge Syncline, a more than 30 km long NWW-SEE trending structure with depths greater than 3000 m and minor faulting at its edges which may still propagate to the central and hence deeper parts of the syncline to promote preferential fluid pathways and thus be suitable for the exploration for geothermal energy.

– The analytically calculated temperatures in the subsurface reach values above 150 °C for the deepest reservoir sections and are thus suitable to extract heat from the subsurface to supply the residential and commercial sector directly or with the use of heat pumps and to provide heat for industrial processes.

– The uncertainties associated with the structural geological model ranging between 23 m (Base Lower Cretaceous) and 696 m (Base Lower Bunter) and temperature distributions (e.g. 85 to 151 °C, median temperatures of the Middle Bunter) outline the necessity of exploration activities to reduce those uncertainties to decide on a utilization concept for the thermal power that can be produced in the end.

– Stochastic simulations of two potential geothermal reservoirs show that the shallower and therefore cooler but more permeable Keuper reservoir results in geothermal power outputs between 2.3 MW (P90) and 14.3 MW (P10) compared to 1.8 to 11.3 MW in the Bunter.

Our results indicate multiple potential geothermal reservoirs at different depth intervals in the subsurface of Minden and provide the structural geological basis for further numerical modeling applications and exploration activities in the future. The calculation of the geothermal potential for a single doublet system yields bandwidths of geothermal power outputs for the different reservoirs. The number of doublets may be scalable along the mapped structure to develop a geothermal system in the subsurface of Minden and surrounding areas to provide geothermal energy for the domestic, commercial and/or industrial sectors.

be requested from LBEG or GD NRW for further scientific or commercial purposes.

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