Hydraulic Characterization of Potential Geothermal Reservoirs in the North German Basin

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ABSTRACT

This study investigates the geothermal potential of sandstone formations in the North German Basin that could play a key role in Germany's turn-around in heat production and supply ("Wärmewende"). Currently, there only exist two sites in the eastern part of the North German Basin where geothermal energy is used for district heating.

The focus of this study, which is funded by the Federal Ministry for Economic Affairs and Energy (BMWi) in the project Geofaces, are the Dogger and Lower Cretaceous sandstone formations in the western part of the North German Basin. These formations are widely distributed with a mean thickness of more than 10 m and in depth greater than 800 m below ground level. Besides the temperature of a geothermal reservoir, especially the permeability of the rocks is of importance.

A combined investigation of hydraulic measurements of porosity and permeability of plugs together with data derived from geophysical borehole measurements and the modeling of the temperature of the Dogger is carried out with the aim to assess the permeability distribution and its geothermal potential. The permeability will be mapped using the ordinary kriging method. Finally, these maps will be integrated into the geothermal information system (GeotIS).

The additional data will help project planners to estimate the low enthalpy geothermal resources in the western part of the North German Basin. In combination with other parameters like for instance depth, it will be possible to distinguish between favorable and less favorable sites for geothermal exploration.

Preliminary results show favorable regions northwest of Hanover in the center of Lower Saxony and in the eastern part, as well as a few kilometers south of Hamburg.

1. INTRODUCTION

In Germany, approximately 54% of the primary energy consumption is spent for heating and hot water (Federal Ministry for Economic Affairs and Energy (BMWi) 2018). Therefore, geothermal energy should play a major role in the heat turn-around ("Wärmewende"). Unfortunately, geothermal resources in Germany are limited to intermediate and low enthalpy resources (below 200 °C), which are used up to now predominantly for district and space heating, balneological applications and only at some sites for power production (Agemar et al 2014).

In Germany, the Upper Rhine Graben and the South German Molasse Basin yield the highest geothermal energy production in Germany, followed by the North German Basin with currently two major productive sites at Neustadt-Glewe and Waren, and one in construction at Schwerin (GeotIS 2019). This study investigates the geothermal potential of sandstone formations in the North German Basin that could play a key role in Germany's turn-around in heat production and supply. In this context, the North German Basin is often referred to as a sleeping giant. Although huge in dimension, very few geothermal installations tap thermal water from the deep subsurface in this area.

Therefore, it is the aim of this study to characterize the hydraulic parameters of two major potential geothermal reservoirs, the Lower Cretaceous and Dogger siliciclastic sediments, in the western part of the North German Basin. The focus on the Dogger sediments is the characterization and mapping of the hydraulic subsurface and temperature distribution, whereas the focus on the Lower Cretaceous study is the influence of geological boundaries on hydraulic properties, because Kuder et al (2014) already mapped the hydraulic distribution.

1.1 Geothermal aquifers in northwest Germany

The Miocene geology of northwest Germany is controlled by the development of the North German Basin. Due to the ongoing subsidence since the middle Paleocene and contemporary tectonic movements, several sub-basins formed (Voigt et al., 2008). The Lower Saxony Basin is one of these sub-basins. It existed from the Permian to the Late Cretaceous and became inverted in the course of the Alpidic

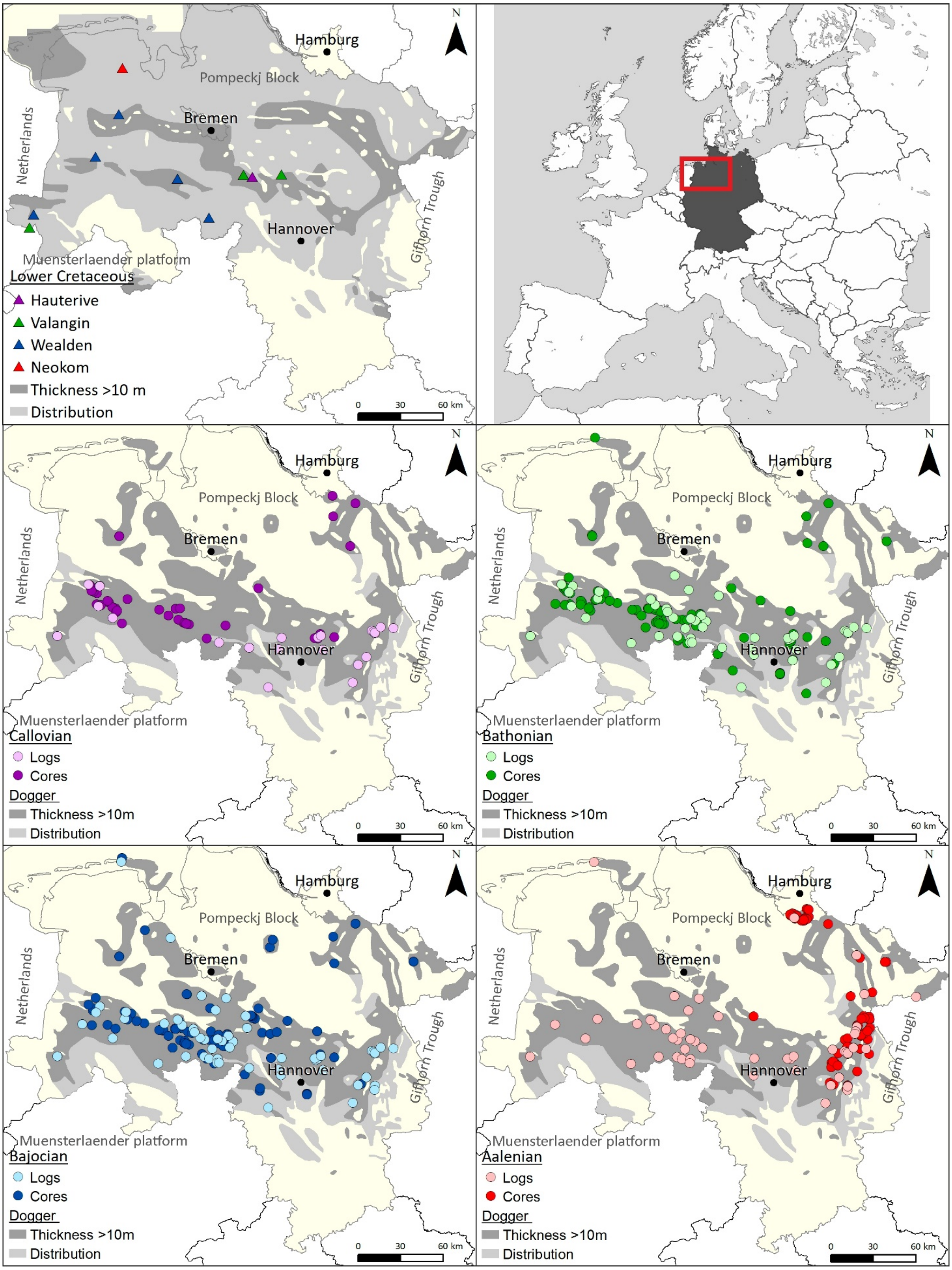

Fig. 1: Dataset of this study split in different stratigraphic formations of Lower Cretaceous and Dogger formations in Lower Saxony. Distribution of Dogger and Lower Cretaceous sediments in northwest Germany after Knopf (2011). The dark grey areas show sandstones with a thickness of more than 10 m and a top depth of more than 800 m. Study area is marked by red rectangle.

Orogenese. The Lower Saxony Basin covers wide areas of Lower Saxony and is bordered to the north by the Pompeckj Block, to the west approximately by the Dutch-German border, to the south by the

Muensterlaender platform and to the east by the Gifhorn Trough (Betz et al 1987; Voigt et al 2008) (Fig. 1). Due to salt-tectonics different salt structures, e.g. domes, developed and influenced the geologic strata (Trusheim 1957). In 2011, the Geological Survey of Germany (BGR) compiled maps of potential reservoirs in the western part of the North German Basin (Knopf 2011). It was pointed out that the Jurassic Dogger as well as the Lower Cretaceous with average depths between 1200 m and 400 m offer the most promising reservoirs (Knopf 2011).

Dogger sediments occur in a west-east running band in the Lower Saxony Basin, which is part of the North German Basin. Most of the deposited sandstones are thicker than 10 m and the top is deeper than 800 m (Fig. 1). Deposition took place on a fluvial dominated deltaic system into a shallow coastal sea, where sandstones formed in distributary channels and on sandsheets on the delta plain (Betz et al 1987; German Stratigraphic Commission 2016; Zimmermann et al 2018). The sediments are mainly fine-grained sandstones and claystones. The most important aquifers are the Dogger beta sandstones of the Aalenian, the Bajocian Garantianen sandstone as well as the Cornbrash-facies and the Wuerttembergica sandstones of the Bathonian (Brand and Mönning 2009; Knopf 2011) (Fig. 2).

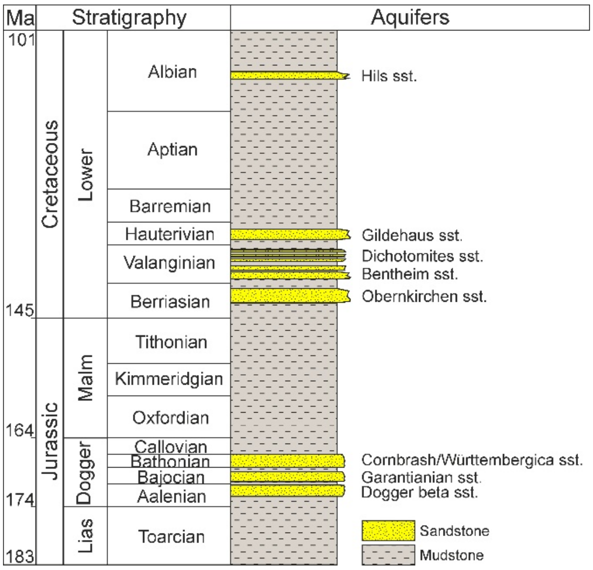

Fig. 2: Cretaceous and Jurassic stratigraphy modified after Brand and Mönning (2009); Feldrappe et al (2008); Mutterlose (2000) for the western part of the North German Basin. Ages adjusted after German Stratigraphic Commission (2016). sst. = sandstone.

Lower Cretaceous sediments are wide spread in Lower Saxony except in the southern part and west of the Harz. Accumulated sandstone thickness of 10 m and more meters with a top depth of more than 800 m occur only in a NW-SE stretching area and in form of patches (Fig. 1). Siliciclastic deposition took place in a fluvial braided river-system that lead to a heterogenic facies distribution (Schulz and Röhling 2000). The sediments are mainly build of intercalations of fine-grained sandstones and siltstones with clayey layers. Partially conglomerates can occur. The most important aquifer sandstones are the Berriasian Obernkirchen sandstone, the Valanginian Bentheim and Dichotomites sandstones, the Hauterivian Gildehaus sandstone (Mutterlose 2000) as well as the Albian Hils sandstone (Knopf 2011), which occurs only in the southeastern part of Lower Saxony (Fig. 2). Sometimes data is only available under out-dated nomenclature and cannot be assigned unambiguously. For that reason, the Neokom comprises data from the Valanginian to the Barremian.

2. DATA AND METHODS

A combined investigation of hydraulic measurements of porosity and permeability of plugs together with data derived from geophysical borehole measurements was carried out in order to assess the spatial permeability distribution.

Digital data from hydrocarbon wells stored in the Geothermal Information System (GeotIS) as well as analog well data (logs) in the archives of the Geocenter in Hanover form the basis of this study. Altogether, the Dogger data set consists of about 225 plug measurements from 200 locations and of about 150 additional data from log interpretation in 72 locations. The Lower Cretaceous data set consists of about 15 plug measurements in 10 locations. A thorough analysis of self-potential- or gamma-ray-log together with a neutron-, density- or sonic-log has been accomplished. The Geolog software from Paradigm has been used to estimate porosity and permeability values where core samples are not available. The permeability distribution has been mapped using the ordinary kriging method.

The 3D temperature model of the GeotIS geothermal information system, which was updated in 2018, was used to estimate the formation temperatures at the base and top of the Dogger. This temperature model was calculated using 3D universal kriging based on subsurface measurements available in FIS-Geophysics (another information system run by the LIAG) and soil temperatures, which were determined from average air temperatures 2 m above ground. The methodology largely corresponds to the procedures described in Agemar et al (2012), but the distance rules for the quality filter have been modified for data selection and a further quality category for temperature measurements by pump tests has been introduced. Studies have shown that temperature measurements from pump tests often do not reflect the undisturbed formation temperature as reliably as reservoir temperatures or equilibrium logs, but are generally better than corrected bottom hole temperatures (BHT). The temperature measurements are divided into 4 quality categories:

1. equilibrium logs and reservoir temperatures

2. temperature measurements during pump tests

3. disturbed logs and corrected BHTs with known shut-in times

4. corrected BHTs with estimated shut-in time

The distance rule states that less reliable measurements up to a certain distance from a more reliable measurement are not used if they are not located more than 500 m lower than the measurement of higher quality. Measurements of the second quality category shall not be used within a radius of 5 km of a measurement of the highest category 1. For category 3 measurements, the radius shall be 10 km and for category 4 measurements the radius shall be 20 km.

3. RESULTS

3.1 Dogger

Regarding the median values, highest porosity values occur in the Aalenian and Bajocian formations, followed by Callovian sandstones. Poorest porosity values are found in the Bathonian sediments. The median permeability values are also highest in the Aalenian sandstones. The median permeability values of the sediments of the Callovian, Bajocian and Bathonian formation are much smaller (Fig. 3).

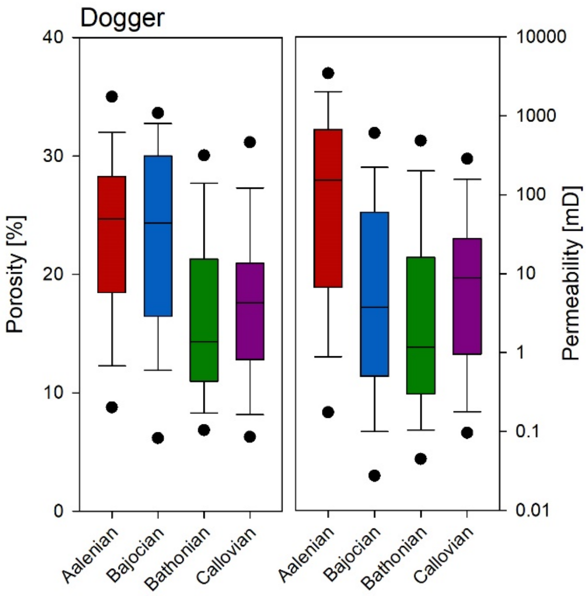

Fig. 3: Boxplots with median as well as 5th and 95th percentiles of porosity and permeability data for sandstone intervals in the Dogger formations.

Altogether, porosity and permeability values cover a wide range, indicating very good to very poor reservoir potential. The permeability maps show spatial variations in all formations (Fig. 4). In the Aalenian sandstones, highest values occur in an east to northwest running arc from the eastern border of the study area to Hamburg and northwest of Hanover near the city of Nienburg in the center of Lower Saxony. Aalenian temperatures are also mostly about 70 °C, but several regions with temperatures up to 140 °C exist. The Bajocian permeability distribution also shows a favorable region in the center of Lower Saxony, which is even larger, and shows overall higher permeability values in that region than the Aalenian values. Furthermore, scattered values with high permeability values occur in the Bajocian spatial distribution. The Bathonian sediments also show most favorable values in central Lower Saxony in a west-east running band from Nienburg to Hanover. The dataset is smallest in the Callovian. Therefore, only scattered and isolated high permeability values occur. Spatial trends are not distinguishable. Callovian temperatures are mostly about 70 °C. Locally, temperatures up to 140 °C occur.

Another, more sophisticated approach for mapping hydraulic properties is based on the application of geostatistic methods. The ordinary kriging method has been applied on Bajocian median permeability values. Only areas with a normalized kriging variance up to one were considered. The maps show areas with high permeability in the central and northeastern parts of Lower Saxony (Fig. 5). In the western parts single higher values occur.

Interpretation and discussion

In the project area there are several regional positive temperature anomalies along a line between Lingen and Celle, which, however, are not due to ascending deep groundwater, but most probably to differently heat conducting sediments in the Lower Saxony basin (Agemar et al 2012). These anomalies manifest themselves locally in temperatures up to 30 °C higher than expected. However, the depth of the aquifer is still the main controlling factor for the temperature (Fig. 4).

In comparison with the Bajocian facies map from Franz et al (2015), the high permeability values of this study occur mainly in the distributary channel belt and mouth bar complex deposits (Fig. 4). These deposits coincides with high reservoir potential from the study of Franz et al (2015). There are only a few isolated high permeability values in the western and in the eastern parts, which seem to be not facies dependent. For these isolated parts detailed local investigations are necessary.

Overall, the kriging map shows the same features as the facies maps, but the spatial influence of single values is too high. The kriging algorithm averages over spatial distances, regardless of the geological structures. Furthermore, different data quality, e.g. permeability from plug measurements vs. log interpretation, is not regarded. All values are equally considered.

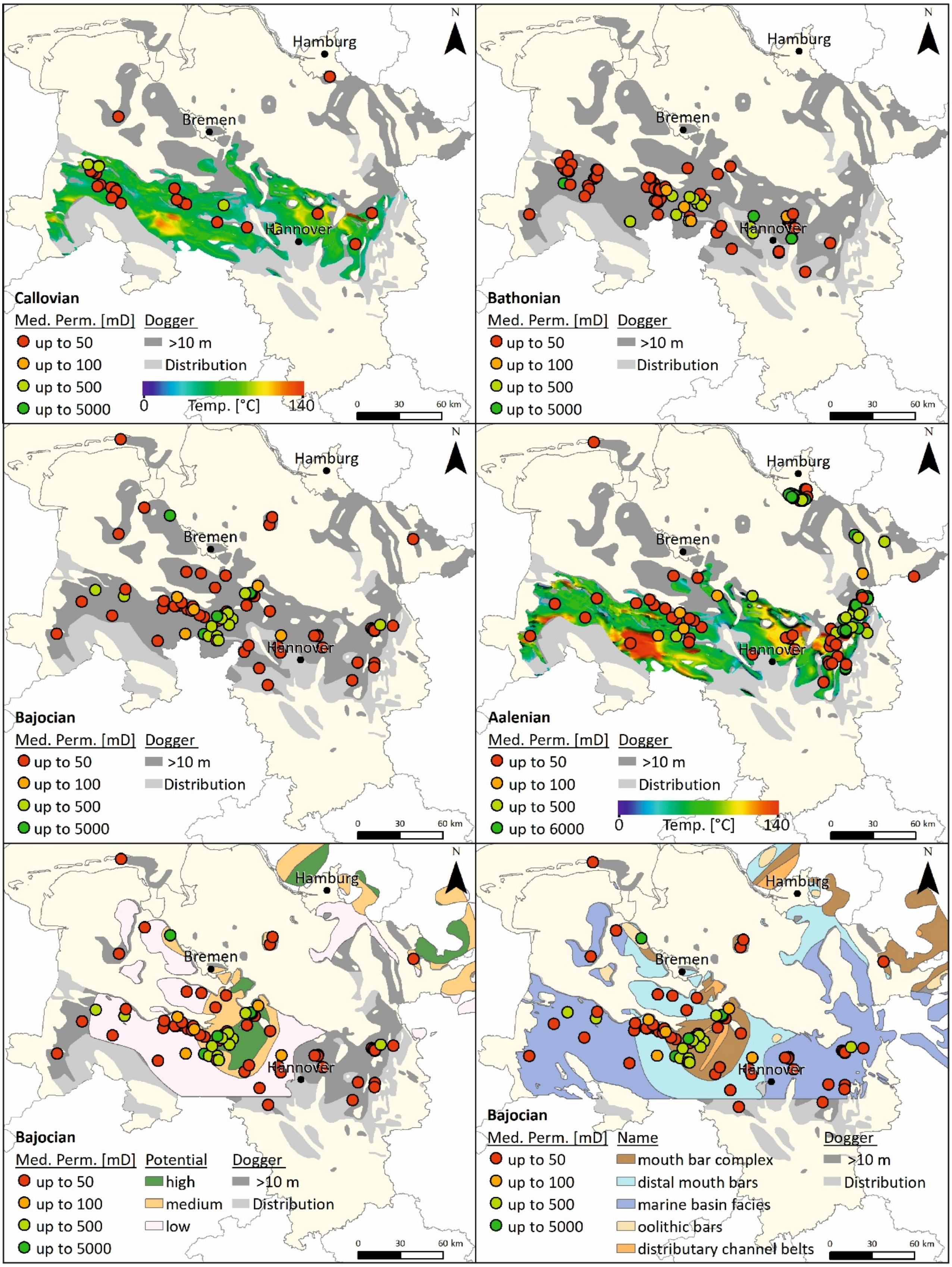

Fig. 4: Dogger formation maps of median permeability. Combined data from plug measurements and log interpretation. Dogger distribution after Knopf (2011). Dark grey areas show sandstones with a thickness of more than 10 m and a top depth of more than 800 m. Furthermore, the temperature distribution for top Dogger (Callovian Formation) and base Dogger (Aalenian Formation) is modelled in the study area. Maps on the bottom also show the reservoir potential (left) and facies (right) from Franz et al (2015).

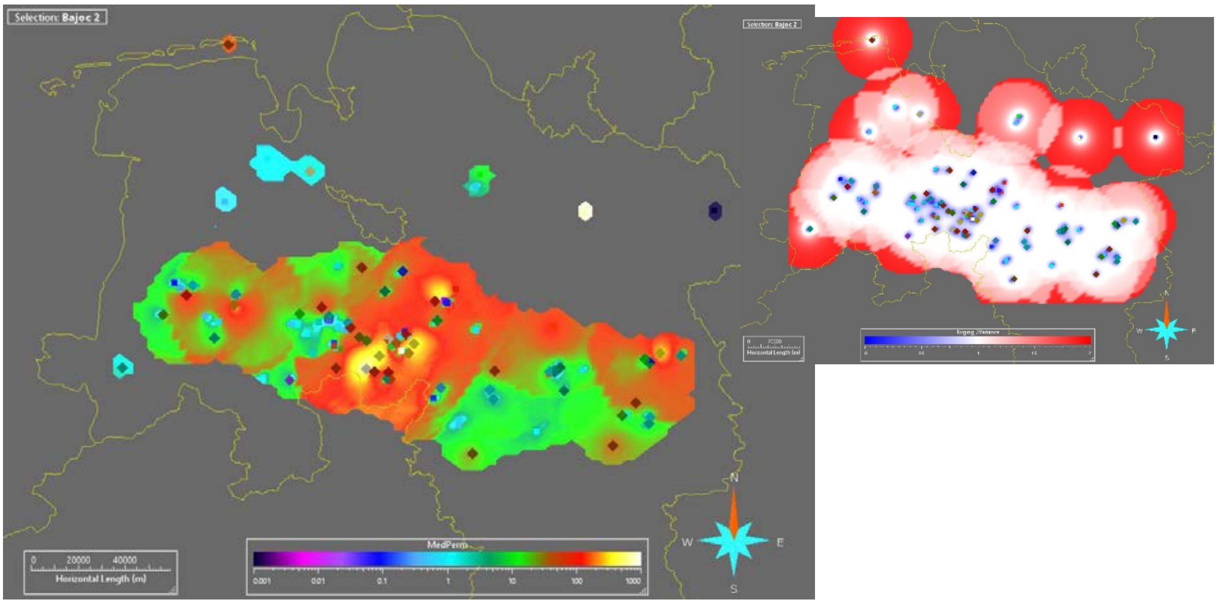

Fig. 5: Distribution of Bajocian hydraulic parameters with ordinary kriging method. Variance distribution on the upper right side.

3.2 Lower Cretaceous

Mostly, hydraulic parameters in geological well reports are given for an interval and not for one specific depth. In order to assess the influence of stratigraphic boundaries, as transgression or hiatus surfaces, on hydraulic properties only data with less than 10 m distance to a stratigraphic boundary and with an interval length of maximum 10 m are considered.

At transgression and hiatus surfaces, the investigated geophysical logs show only total porosity, the effective porosity is zero or is not determinable and therefore no permeability estimation is possible. Only core measurements and total porosity values are available.

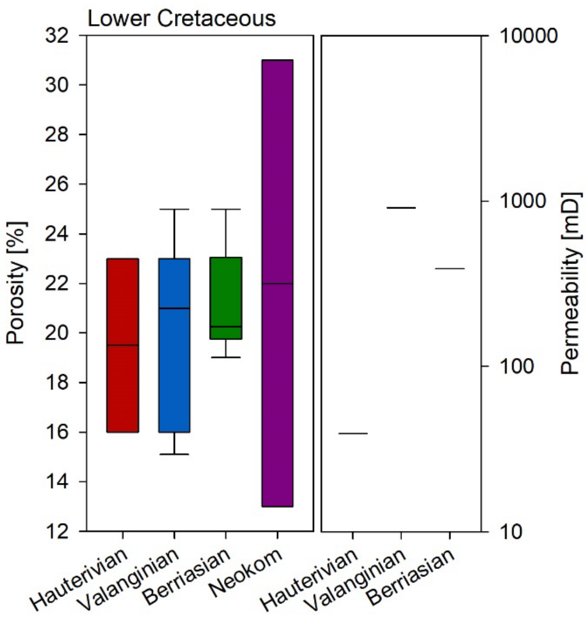

Fig. 6: Box-Whisker plots of Lower Cretaceous porosity and permeability data.

The plug porosity values, which are all measured within a distance of 0.5 to 10 m to the stratigraphic boundary, are between 13% and 31%. Highest median values occur in the Neokom, but with only two data points and a very wide span, followed by Valanginian, Berriasian and Hauterivian values with a much smaller data span. The distribution of the permeability data is the same as for the porosity data, but only three values are available. The highest value occurs in the Valanginian, followed by the Berriasian formation and the minimal permeability value is of Hauterivian age (Fig. 6). With depth, a slight decrease in porosity is visible (Fig. 7). The sandstones are mostly fine grained and fine to medium-grained sandstones. Coarser sandstones show low porosity values as well as high porosity. The fine-grained sandstones show medium porosity values. A correlation between porosity and grain size is not visible (Fig. 7).

Interpretation and discussion

It could be possible that the investigated transgression and hiatuse surfaces have a sealing influence because effective porosity cannot be derived from geophysical logs. However, porosity median values, measured within a distance of 0.5 to 10 m to the stratigraphic boundary, and the few permeability values from core plugs are in the range suitable for geothermal utilization. Porosity values are independent of grain size, but decrease slightly with depth. That is usually due to compaction and burial depth. Permeability data is too scarce for an interpretation, but the porosities are high in the Valanginian and Berriasian sandstones, next to the transgression and hiatus surfaces. However, boundaries itself are not sampled. Therefore, it is only possible to assume that if the transgression and hiatus surfaces are sealing, that effect will not reach far into the surrounding sediment.

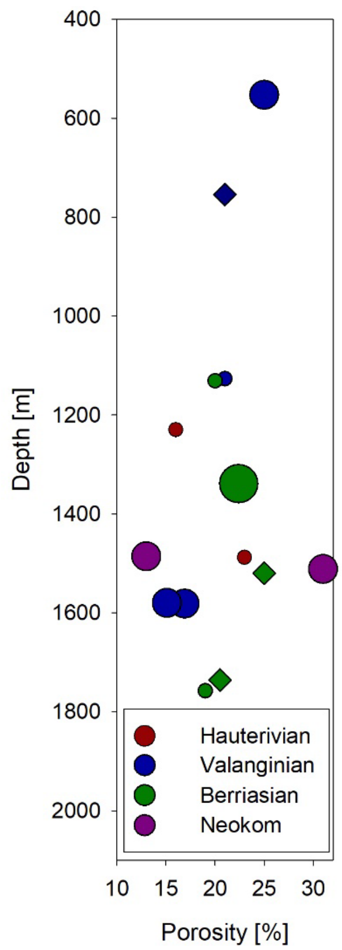

Fig. 7: Cross plot of porosity data with depth. The size of the circles reflects the grain size. Diamond shapes represent data without grain size values.

4. SUMMARY AND OUTLOOK

Main results of the Dogger sediments are:

- Highest permeability values occur in Aalenian sandstones.
- Bathonian and Bajocian sediments show highest permeability and porosity values in the center of Lower Saxony, whereas the Aalenian sediments are most suitable for geothermal applications in the eastern part.
- Temperature anomalies in temperatures up to 30 °C higher than expected exist, but the depth of the aquifer is still the main controlling factor for the temperature.
- Callovian temperatures are mostly about 70 °C. Locally, temperatures up to 140 °C occur. High permeability values (>50 mD) do not coincide with high temperatures.
- Aalenian temperatures are also mostly about 70 °C, but several regions with temperatures up to 140 °C exist. High permeability values do not coincide with high temperature or a located outside the temperature model area.
- Bajocian sediments show high permeability and porosity properties that coincide with distributary channel belt and mouth bar complex deposits.
- The spatial distribution of the Bajocian sediments was mapped using the ordinary kriging without weighting of log- and plug-derived values. Geological structures, which could influence the subsurface distribution of permeability as for example faults or salt domes are not yet considered.

Main results of the Lower Cretaceous sediments are:

- Permeability estimation with logs is not possible.
- Porosity values are independent of grain size, but decrease slightly with depth.
- Permeability data is very sparse.
- Best permeability values occur in the Valanginian.
- However, stratigraphic boundaries themselves were not sampled. Therefore, it is only possible to assume that if the stratigraphic boundaries are sealing, that effect will not reach far into the surrounding sediment.

The additional data will be integrated into the geothermal information system (GeotIS, https://www.geotis.de) and help project planners to estimate the low enthalpy geothermal resources in the western part of the North German Basin.

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