# EVALUATING POTENTIAL GEOTHERMAL RESERVOIRS IN NORTHERN GERMANY BY INTERPRETING NMR AND CT RESULTS OF CORE PLUGS AND SIDEWALL CORES

Hübner, W., Orilski, J., Halisch, M., Wonik, T.
Leibniz Institute for Applied Geophysics, Stilleweg 2, 30655 Hannover, Germany

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## ABSTRACT

In northern Germany geothermal energy is available at depths of less than five kilometers from tight sediment reservoirs. An effective access of these hot reservoirs by a single deep well is tied to a high porosity and permeability of the sediments. If the matrix permeability proves to be insufficient, heat exchange areas can be created by hydraulic fracturing. To test the concept a demonstration well (almost 4000 m of depth) was drilled in midst of the city of Hannover. Drill cores as well as sidewall cores were extracted from potential sandstone strata to evaluate their reservoir capacities.

In addition to standard petrophysical parameters (such as porosity and permeability) $T_2$ relaxation time distributions were determined by low field NMR and compared with 3D CT images of the pore space. The results have been interpreted with regard to pore size distributions. Besides characterizing the pore space, the influence of micro fractures and brine on the results of laboratory core analysis has been studied.

Especially plugs of high compaction and density showed fractures, which were probably induced by the drilling process. Their influence on permeability was significant. NMR measurements reacted more insensitive, approving the assumption that for possibly fractured plugs the calculation of permeability from NMR data might be more reliable than results from direct permeability measurements. Due to formation waters and drilling mud of high salinity some of the plugs and all of the sidewall cores contained remarkable amounts of salt. Its influence on permeability and porosity was detectable but insignificant for pore size distributions determined by NMR.

Overall strata of high reservoir quality were found in depths of about 1200 m (Lower Cretaceous). Sandstones of older periods are characterized by very low porosities and permeabilities. Although reservoir capability therefore is low, successful fracturing might create a sufficient exchange area to enable the extraction of geothermal heat.

## INTRODUCTION

In 2009 a deep drilling project was started in midst of the city Hannover, Germany. Its aim was exploring the possibilities of extracting geothermal heat which is stored in tight sandstone reservoirs in depths of less than five kilometers in northern Germany. For successful realization of such a geothermal project high temperatures at the destination depth are essential. Furthermore the heat must be accessible. This means either the rock by itself proves to have a sufficient porosity and matrix permeability to enable the push of cold and the extraction of hot water or the necessary heat exchange area must be created by hydraulic fracturing.

During the drilling operation the formations of Cretaceous, Jurassic and Trias were penetrated until the final depth of 3901 m was reached. Especially the abundant Cretaceous and Triassic sandstone formations were of high interest. To estimate their reservoir qualities, rock cores of a length of about 15 m were extracted from the Wealden formation (Lower Cretaceous), the Detfurth formation and the Volpriehausen formation (both Lower Triassic: Middle Bunter). In addition 23 sidewall cores were taken by a mechanical tool from the Wealden, a Jurassic Sandstone (Dogger) and an Upper Triassic Sandstone (Keuper). Sample plugs from all formations were analysed in terms of relevant petrophysical parameters, which are pore space dependent average characteristics such as porosity and permeability.

## MATERIAL AND METHODS

From the original cores about 100 samples, mainly cylinder with a diameter of 3 cm and a length of 4 cm were prepared. The plugs of the Wealden formation covered all lithologies abundant within the rock core, which were sand, fine sand, clay and coarse clay. Nine sidewall cores, taken from a thick Wealden sandstone bank below the cored area, eight sidewall cores from the Dogger bank and six from the Keuper bank were studied, as well as 24 plugs from the Middle Bunter core. The samples of Dogger, Keuper and Middle Bunter were characterised by a high content of clay.

The grain density was determined by a helium Pycnometer after initial drying. The permeability measurements were done anisotropic (except for the sidewall cores) by using a Fancher-type cell under ambient conditions. Ambient conditions were chosen because permeability measurements under stress on some samples of the middle bunter showed that there was no significant change in permeability, which was already very low, with rising pressure. The porosity was calculated by conventional buoyancy method. In addition $T_2$ relaxation time distributions were obtained from the results of low field NMR measurements (0.2 T). To get an impression of the pore space micro CT was done on some sidewall cores as well as on samples of 2 mm diameter, drilled from the original cores.

# RESULTS

## Influence of Salt

Within the sidewall cores, the content of salt was extraordinary high, due to the high salinity of the drilling mud. However, prior to the desalination process, the sidewall cores were studied by NMR. After desalination buoyancy measurements were performed and NMR relaxation time measurements repeated.

The $T_2$ relaxation time distributions determined from the NMR CPMG measurements for four sidewall cores of the Wealden, four of the Dogger and three of the Keuper formation are shown in Figure 1. The relaxation time distributions of the Wealden samples clearly differ in the mean value of $T_2$ from those of the Dogger and Keuper sidewall cores (see also Table 1). Interpreting $T_2$ distributions as pore size distributions lead to the assumption that there are by far larger pores in the Wealden samples than in the samples of the other formations of greater depths. The results of micro CT measurements prove that large pores are by far more abundant in the Wealden samples (Figure 2).

Regarding the content of salt, the differences in the relaxation time distributions are small. They are only apparent in the relaxation time distributions of the Wealden sidewall cores, where the $T_2$ distributions measured after desalination are slightly shifted to shorter relaxation times. Such a shift might reason from a reduction of the total amount of large pores (long relaxation times) or an increase in the amount of small pores (shorter relaxation times). The former is unlikely to result from the desalination process, thus, the total amount of small pores increases probably due to the salvation of the salt within small pores or pore throats, connecting to small pores, leading to an overall shift of the $T_2$ distributions to shorter relaxation times. However, the differences are minor and regarded as insignificant for pore size distributions determined by NMR.

Porosities from NMR FID measurements on saline and desalted sidewall cores differed up to 3 %. The increase in porosity after desalination, however, may not only be ascribed to the risen amount of small pores but only to the fact that the saline sidewall cores might not have been fully saturated.

## Petrophysical Characterization of the Samples

In Table 1 the mean values of porosity determined from buoyancy method, directional measured permeability (ambient conditions), grain density and mean $T_2$ of the sandy plugs from all formations are listed. The results of the measurements of the Wealden plugs, prepared from the drill core, mirror their heterogeneity in lithology. The clayey samples show lower porosity, lower mean relaxation time, lower permeability and higher grain density values than the sandy samples. Regarding only the sandy plugs, the mean value of porosity is 11.9 % ± 2.6 %. Permeability ranges between 1 mD and 700 mD and is strongly anisotropic. In the direction perpendicular to the bedding it amounts only around 20 % of the maximum permeability parallel to the bedding.. However, it has to be noted that the extremely high permeabilities (of about 700 mD) are probably caused by fractures (produced during the drilling process). Our assumption relies on the striking and irregular difference between the permeabilities in both directions parallel to the stratification. Therefore it is assumed that only the permeability measured perpendicular to the stratification is constant reliable. In contrast, the results for the Wealden sidewall cores, which were taken from an abundant sandstone layer, are more consistent in porosity, which is 17.2 % ± 2.2 %, and permeability, which ranges between 1 mD and 350 mD.

The samples originating from the Dogger and Keuper have porosities below 10 % and the samples of Middle Bunter even less than 5 % porosity. In most cases the compaction of the samples was too high for successful permeability measurements. However, the few permeability values which could be determined are much lower than 1 mD. Considering the measured permeabilities as a reference for the most interesting formations Wealden and Middle Bunter permeabilities were also calculated from NMR parameters by using the Timur-Coates equation. For the Wealden plugs the permeability measured perpendicular to the bedding was taken as a reference, because it was most reliable. So the mean value of the calculated permeability of the Wealden Plugs in Figure 3 are lower than the measured mean value presented in Table 1. Plotting the calculated permeabilities against the porosity (Figure 3) mirrors the great variety of the Wealden and the bad reservoir quality of the Middle Bunter samples.

**Influence of Micro Fractures**

As mentioned above, micro fractures posed a problem for the evaluation of the measured permeabilities, especially since they are probably induced by drilling. The extent of the fractures differs from visible to micro fractures with a width of a few microns and mm lengths. Visualizing and checking the continuity of large fractures within some of our samples of extraordinary high permeability was done via CT. An example of a continuous fracture in a plug of the Middle Bunter is shown in Figure 4. Clearly visible is the crac-layer, which was 50 µm wide at most. Unfortunately fractures of smaller dimensions, which are present as scans on smaller plugs showed, can not be detected by CT on the plugs of original size. NMR measurements reacted often more insensitive to the presence of micro fractures. In those cases, the calculation of permeability from NMR data seems more reliable than results from direct permeability measurements.

## CONCLUSION

In consideration of the permeability enhancing influence of continuous, drilling induced micro fractures, the permeability of all Dogger, Keuper and Middle Bunter samples studied in this project, is very low. Since the porosity of these samples also rarely exceeds 8 %, their reservoir quality is very poor. To make use of the geothermal heat stored within this hot dry rock, sufficient heat exchange areas have to be created by hydraulic fracturing then. This seems feasible since fractures were easily induced in the Middle Bunter samples during sample preparation. The Wealden formation with its high permeable and porous sandstones seems adequate for temporary storage of the cooled water as one possible utilization concept describes.

## ACKNOWLEDGEMENTS

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Table 1. Formation of origin, approximately depth, type of sample: plug (Pl) or sidewall core (SC), the associated mean values of porosity, permeability, grain density and $T_2$ relaxation time of the samples from the drilling site in Hanover, Germany.

| formation | mean sample depth / m | type of sample | porosity / % | permeability / mD | grain density / g cm$^{-3}$ | $\langle T_2 \rangle$ / ms |
|---|---|---|---|---|---|---|
| Wealden | 1215 | Pl | 11.9 | 130 | 2.72 | 47 |
| | 1238 | SC | 17.2 | 85 | 2.65 | 117 |
| Dogger | 1700 | SC | 8.5 | 0.1 | 2.84 | 1 |
| Keuper | 2519 | SC | 5.1 | 0.1 | 2.72 | 1 |
| Middle Bunter | 3549 | Pl | 2.7 | 0.2 | 2.68 | 3 |

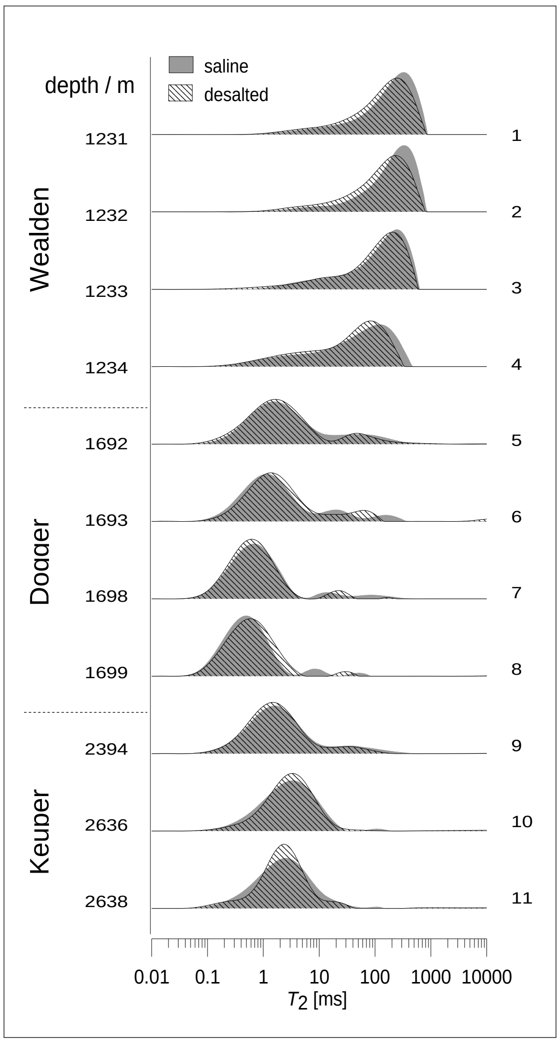


Figure 1. $T_2$ relaxation time distributions of sidewall cores from the formation Wealden, Dogger and Keuper before and after desalination.

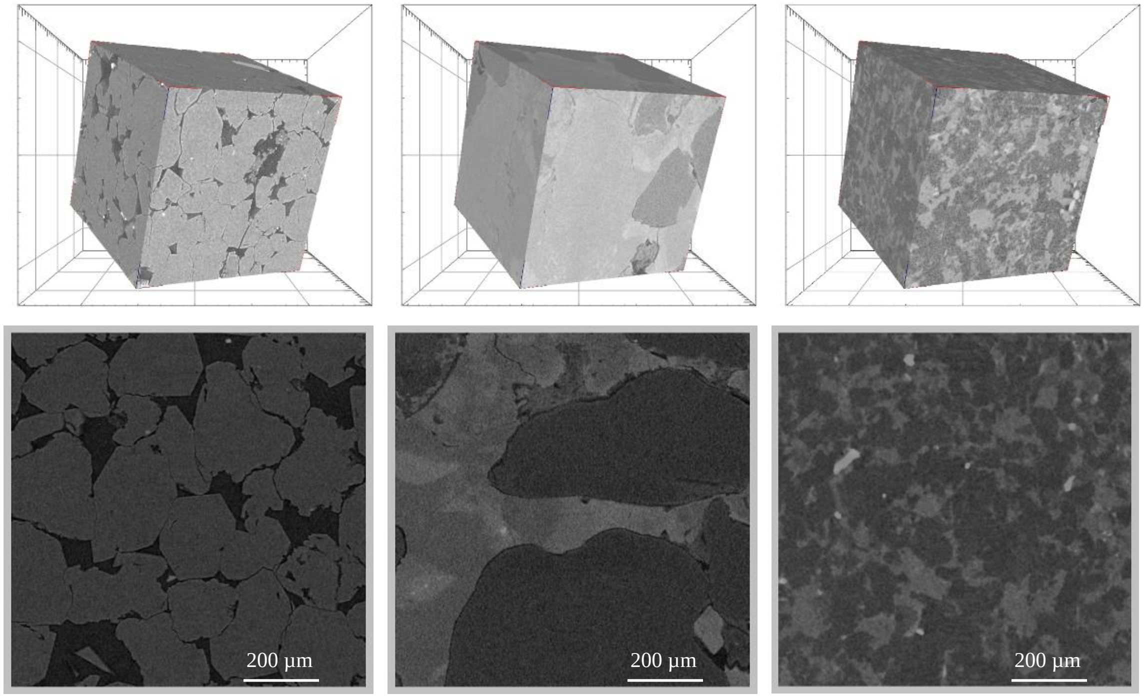


Figure 2. Micro-CT images of a Wealden, Dogger and Middle Bunter Sandstone sample (from left to right). The pore space (colored black) is clearly evident only in the Wealden sample. The achieved Voxel-Resolution is about 1 µm, the volume of the visualized ROI is about 1 mm³.

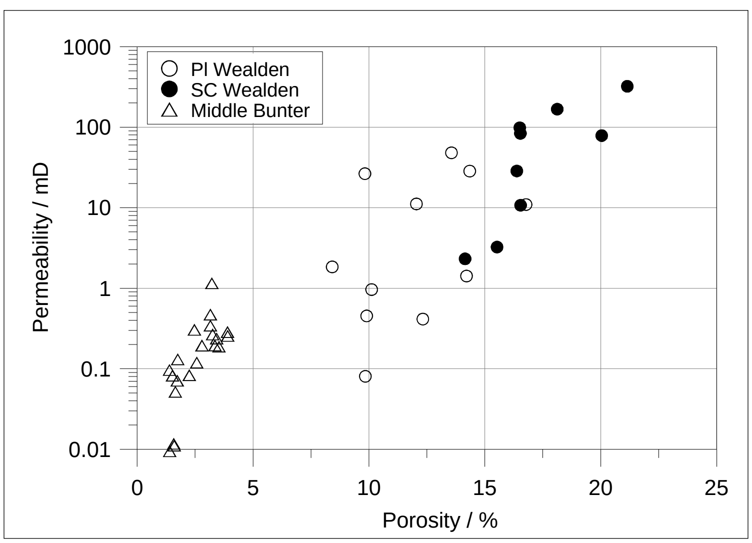


Figure 3. Permeability-Porosity plot for plugs (Pl) and sidewall cores (SC) from the Wealden and plugs from the Middle Bunter formation (permeability calculated from NMR measurements, porosity measured by buoyancy method).

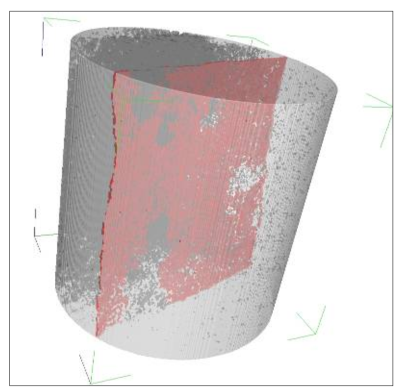

Figure 4. A fractured sample of the Middle Bunter formation: CT image of a cylindrical detail (diameter and length 5 mm).