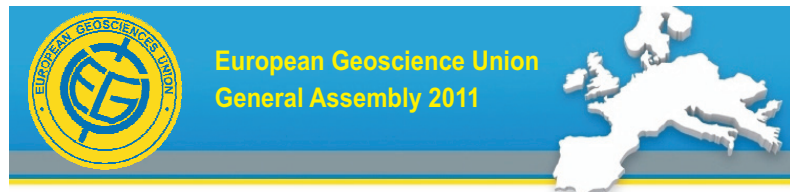


The Rotliegend Reservoir System of the northern Upper Rhine Graben (Germany): From Pores to Production

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Introduction

The geothermal reservoir potential of the Permian Rotliegend sediments and volcanics of the northern Upper Rhine Graben (Germany) has been overseen in past studies. The top of the up to 2 km thick clastic, volcanoclastic and volcanic succession of Rotliegend deposits is known to be at depths of 1 to 3 km in the study area, thus expected to have temperatures of more than 100°C sufficient for hydrothermal utilization.

Here, we present poroperm data of the different Rotliegend rock types sampled from outcrops and drill cores from different depth intervals. Facies and depositional environment, diagenetic history and pore types were also studied petrographically in detail by thin sections to explain the measured differences in petrophysical properties. Additionally, thermal conductivity and thermal diffusivity were measured to provide a reliable geothermal reservoir prognosis.

Petrography

Thin section petrography shows that porosity and permeability in all samples were strongly reduced by mechanical compaction.

The detrital composition of the studied sandstones is variable with a strong lithic component. Besides quartz, feldspars and granodiorite to granite lithic grains that behaved rigid during burial, it contains micas and several other types of lithic components including schist and volcanic grains. These grains are ductile and were severely deformed during compaction from overburden pressure. During a pre-Triassic erosion phase more than 2 km of Rotliegend deposits were eroded in the study area (Henk, 1992), explaining the observed high overburden pressures.

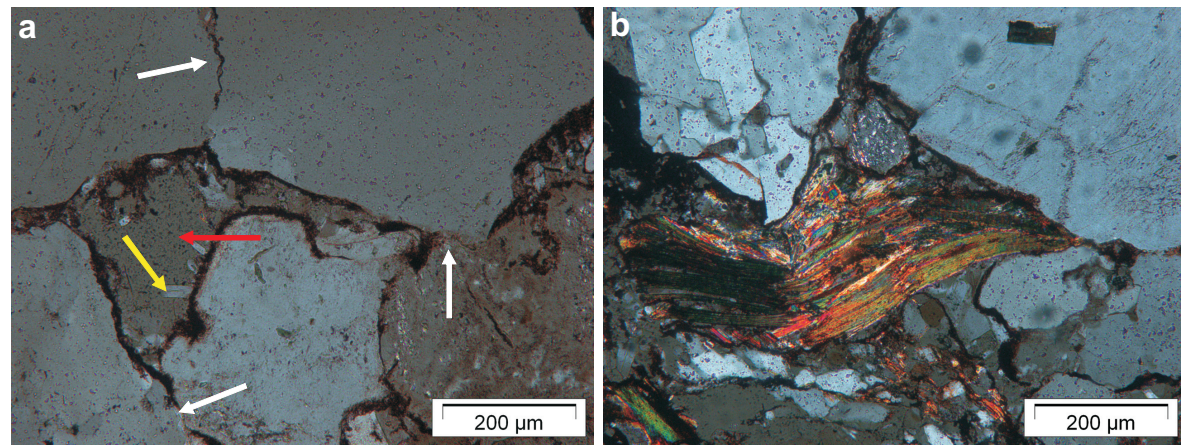


Fig. 1: a) Sandstone of the lower part of the Donnersberg Formation (Rotliegend), which is rich in detrital feldspar and quartz. Due to the rigid grain behaviour some pore space (red arrow) was left during compaction. Close packing of the detrital grains (white arrows) reduce pore connections, which is the reason for the poor permeability. The small feldspar overgrowths (yellow arrow) in the pore do not have much effect on the porosity. b) The sandstone sample of the lower part of the Donnersberg Formation shows a mica grain, which is deformed due to the compaction. Mica has been pressed into the former pore space. Some very small pores are visible between the rigid detrital grains, but they are disconnected.

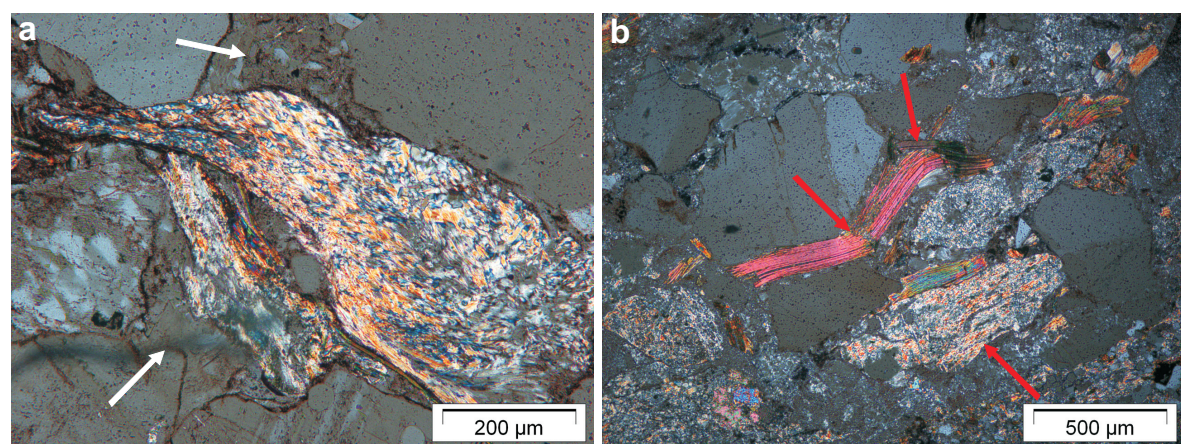


Fig. 2: a) The two ductile lithic fragments from the sandstone of the lower part of the Donnersberg Formation are still recognisable as grains, but one of them is significantly deformed. This type of deformation is characteristic of compaction of ductile grains. Since they are the only ductile grains, surrounded by rigid grains stabilising the grain framework, some pore space is left (white arrows). b) With mainly ductile grains in the sandstone of the upper part of the Donnersberg Formation, the deformation of the individual grains is much stronger (red arrows) and pore space has more or less completely been lost.

At the different sample localities, which belong to the lower and upper part of the Permian Donnersberg Formation, the content of such ductile components is different, causing a difference in the degree of mechanical compaction. In sandstones from the upper part with more ductile detrital grains, the interparticle pore space was largely reduced by the strong deformation of the ductile lithic grains, which in consequence filled all previous open space between the more rigid grains, forming a pseudomatrix. In sandstones from the lower part with less ductile components the interparticle pores were not completely filled by deformed lithic grains. Nonetheless, the content of ductile lithic grains was sufficiently high that the deformation of grains and development of pseudomatrix resulted in a close packing of grains and effectively obstructed pore connections leading to isolated pores. Even though the sandstone still has fair porosity, their isolated and disconnected nature of the individual pores resulted in very low permeability and high thermal conductivity.

Grain leaching has enhanced the porosity in some samples of the lower part. These samples have also the highest measured permeability of up to $1.48 \cdot 10^{-12} \text{ m}^2$ (1499.24 mD) and the lowest thermal conductivity of only $1.36 \text{ W/(m}\cdot\text{K)}$. In these samples, clay infiltration occurred with clay cutan development, which are restricted to the oversized pores and cover authigenic minerals. This is strong evidence that recent weathering caused grain dissolution resulting in interconnected secondary porosity.

In particular the variability in the content of ductile lithic grains determine the petrophysical properties of the Rotliegend sandstones of the Donnersberg Formation. Cementation played only a minor role. This corresponds well to the diagenesis path for shaly sandstones described by Pape et al. (2000) with porosity being first reduced by compaction and only at later stages by cementation and to the osity relationship known for shaly or „unclean“ sandstones (Fig. 4b).

The differences in detrital composition of the sandstone suggest various supply of volcanic material and various clastic source terrains being responsible for the differences in diagenesis and resulting in differences of porosity and permeability.

Care has to be taken, when intending to extrapolate the results of the outcrop study to the reservoir depth. Since clear evidence exists that recent weathering has increased porosity and permeability and therefore the reservoir quality in at least some of the outcrop sandstones, only the data of the unweathered rock samples should be used for extrapolation. It can be assumed, that recent overburden pressures in the reservoir from overlying Quaternary and Tertiary deposits of the graben fill are not much higher than during the primary diagenesis in the Permian.

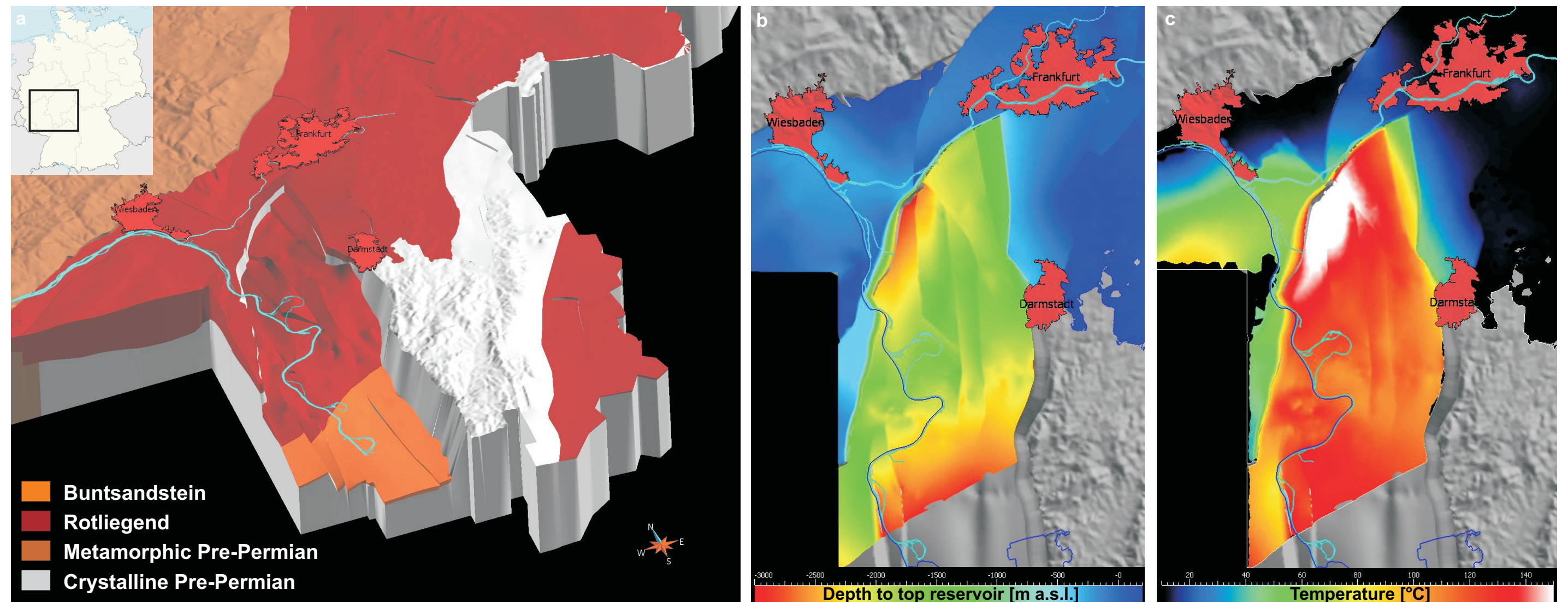


Fig. 3: a) Section of the geological 3D model of Hessen (Germany) (Arndt, 2011). View from southsouthwest onto the Rotliegend Reservoir System (red) of the northern Upper Rhine Graben. The Tertiary and Quaternary graben fill is not shown. The height of the model is 6 km. b) Top view of the northern Upper Rhine Graben showing the depth of the top of the Rotliegend Reservoir System below ground level (Bär et al., 2010). Outcrops of Rotliegend rocks are located between Wiesbaden and Frankfurt and northeast of Darmstadt. c) Top view of the northern Upper Rhine Graben showing the average temperature of the Rotliegend Reservoir System (Bär et al., 2010). Since the average temperature in the graben zone is higher than 100 °C the reservoir is well suited for geothermal exploitation.

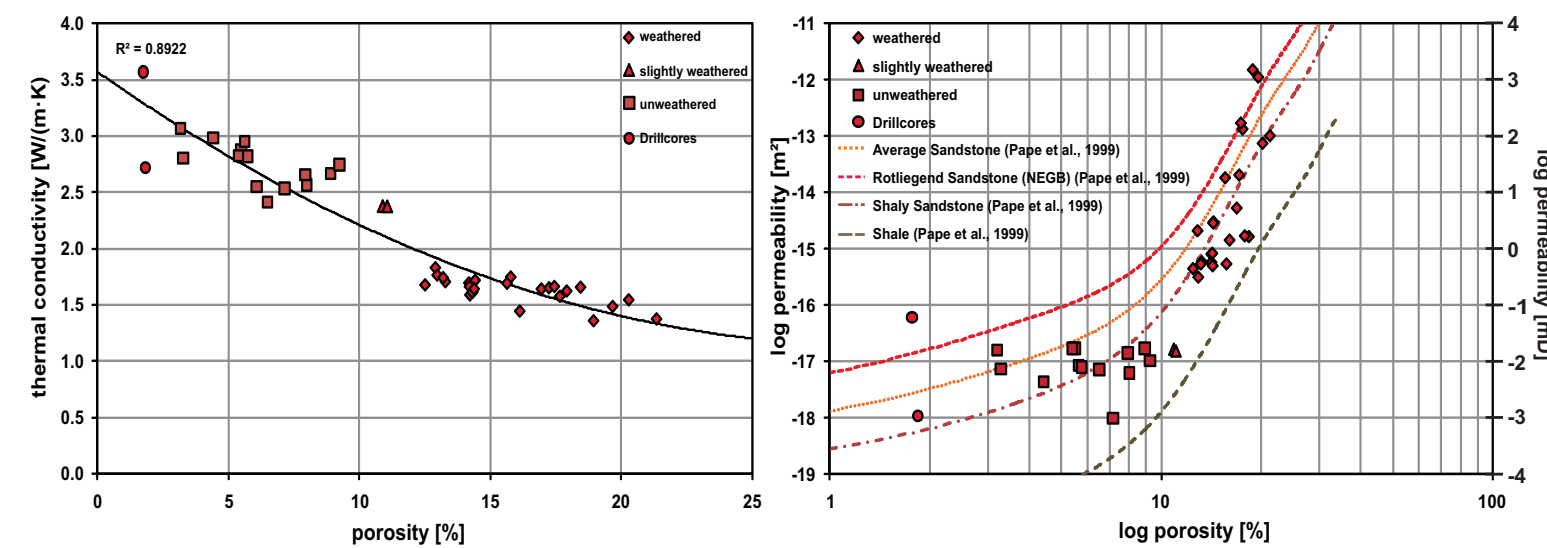


Fig. 4: a) Thermal conductivity versus porosity plot of the poorly sorted clastic rocks of the Rotliegend of the northern Upper Rhine Graben and the adjacent graben flank outcrops, showing a clear correlation between the two parameters. b) Log-log plot of permeability versus porosity of the same set of samples. The given lines defining permeability-porosity relationships are based on the permeability prediction equations based on fractal pore-space geometry by Pape et al. (1999) for different rock types, which were developed amongst others on measurements on Rotliegend sandstones of the northeastern German Basin (NEGB). The scatter in both plots is caused by the differences in grain-size distribution of these proximal deposits.

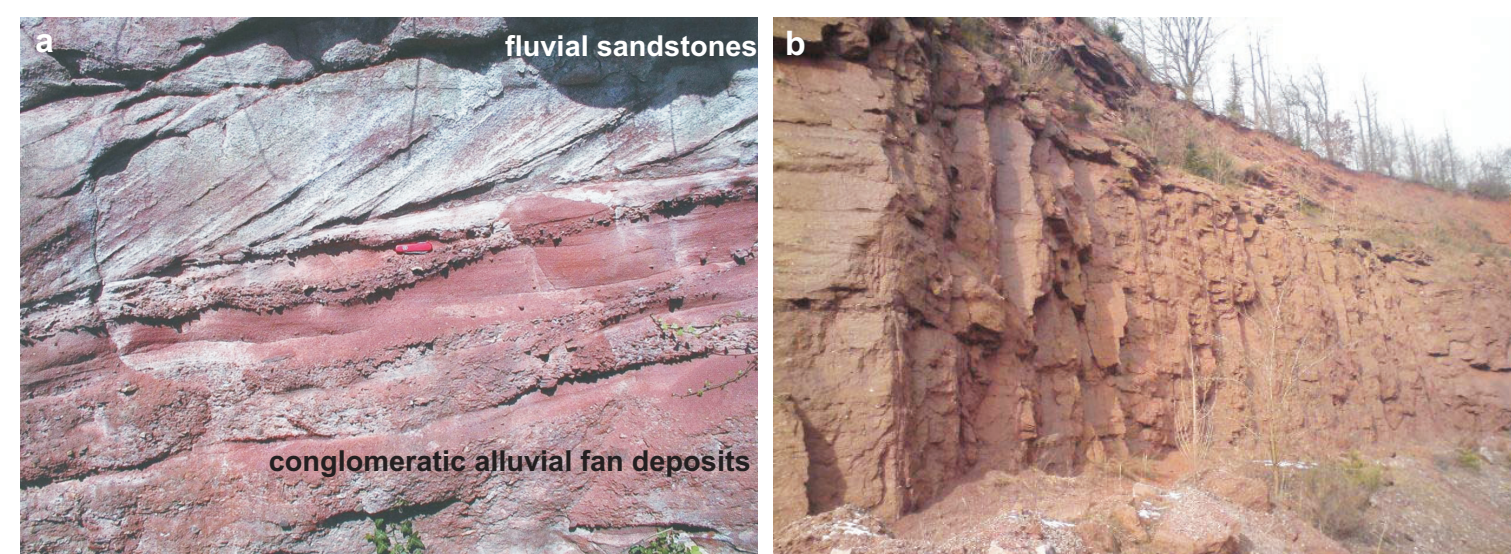


Fig. 5: a) Outcrop photo of a typical Rotliegend succession showing the different facies types (1) fluvial sandstones and (2) conglomeratic alluvial fan deposits. b) Outcrop photo of a typical Rotliegend sandstone (Gottschalk, 2010) illustrating the system of fractures, fissures and bedding planes dominating the rock mass permeability which result in higher hydraulic conductivity than expected by only considering the matrix permeability.

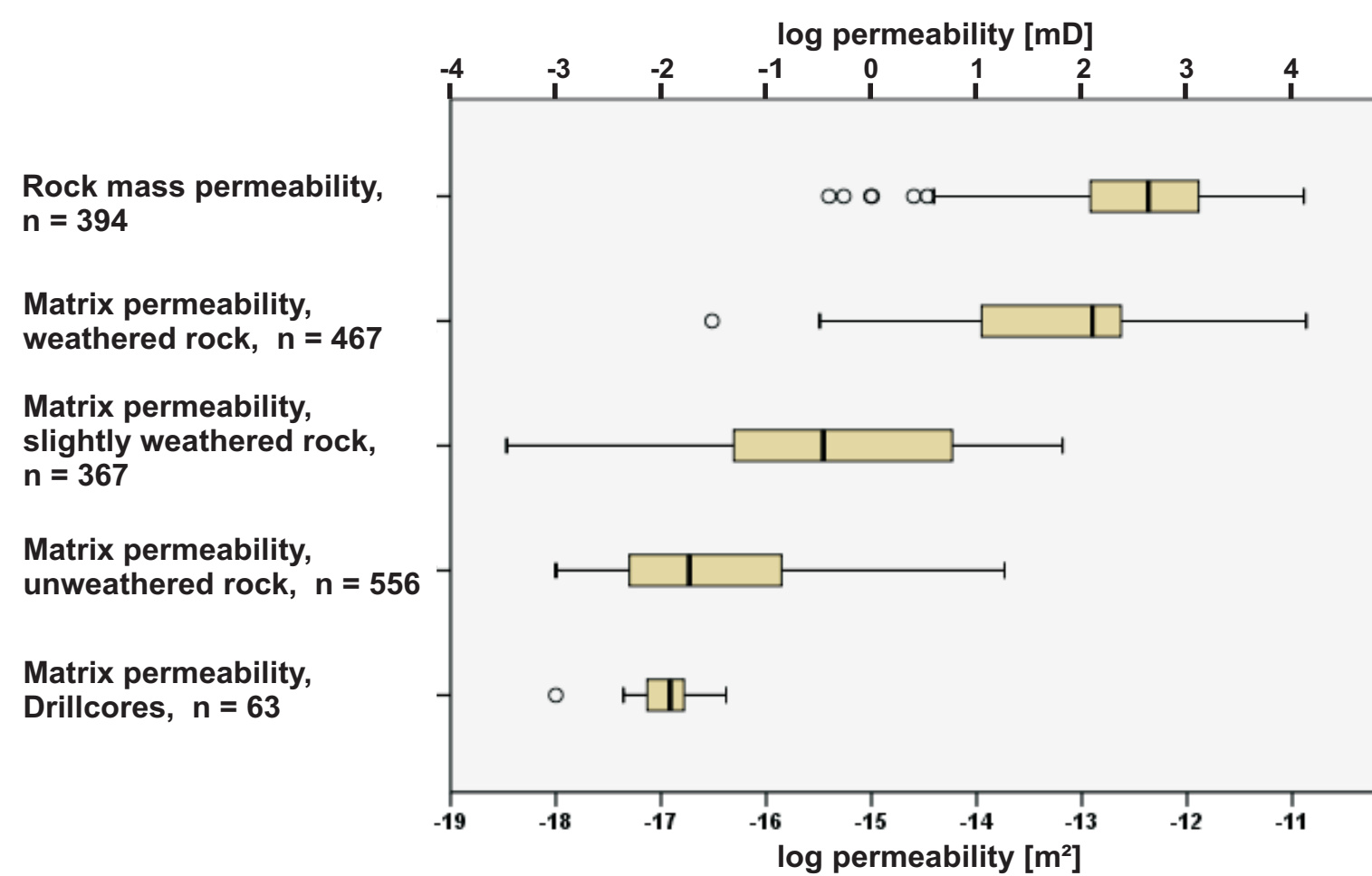


Fig. 6: Box-whisker-plots of rock mass and matrix permeabilities of the Rotliegend Reservoir System of the northern Upper Rhine Graben and adjacent regions. Rock mass permeabilities were determined through the analysis of hydraulic test data of more than 300 water wells with depths of more than 50 m. Matrix permeabilities were measured with a gas-permeameter using both the mini- and the column-permeameter modulus on samples from outcrops and drillcores of different depth intervals.

Outlook

Further investigations will focus on poroperm and hydraulic test data measured by the hydrocarbon industry at the actual reservoir depth of 2 to 3 km to improve knowledge of the matrix and rock mass permeability of the reservoir system and to validate the data and extrapolations from our outcrop analogue studies.

Acknowledgements

We like to thank PanTerra Geoconsultants B.V., Leiderdorp for the kind permission to use their microscope and the thin section photography equipment.

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Geothermal potential

For managing and exploitation of a geothermal reservoir, the reservoir temperature and sufficient production rates of geothermal fluids such as water or steam are the two most important parameters.

The depth and the temperature of the Rotliegend Reservoir System of the northern Upper Rhine Graben is known due to exploration wells drilled by the hydrocarbon industry in the last 50 years and can be extrapolated to greater depths (Fig. 3). Production rates of more than 100 m³/h are necessary for geothermal power generation at economically feasible conditions. To obtain such high production rates, the transmissibility of the supposed reservoir has to be high enough under natural conditions or has to be stimulated artificially by hydraulic fracturing.

The results of the petrographical studies and the poroperm measurements show that matrix permeability and porosity of the Rotliegend rocks of the northern Upper Rhine Graben are not sufficient for geothermal exploitation. However, the Rotliegend reservoir experienced extension-related transfer and strike-slip fault activity already during deposition in an active half-graben basin (Henk, 1993 and Stollhofen, 1998) and later during the formation of the Upper Rhine Graben in the Tertiary. Thus, a well developed fracture system can be assumed (Fig. 5). The hydraulic conductivity of the reservoir is determined by the rock mass permeability, which is dominated by the fracture system rather than by the matrix permeability (Figs. 5 & 6), thus being of less importance for geothermal reservoirs compared to hydrocarbon reservoirs.

This assumption is supported by rock mass permeabilities, which were determined by the analysis of hydraulic test data of more than 300 drinking water wells in the Rotliegend located east and west of the recent graben region with depths of more than 50 m (Fig. 6). Comparisons to the matrix permeabilities, measured using a combined mini- and column-permeameter on samples with different degrees of weathering, show that rock mass permeability is between one and five orders of magnitude higher. Nonetheless, both matrix and rock mass permeability spread over about five orders of magnitude, reflecting the heterogeneity of the Rotliegend deposits and illustrating the need for detailed investigations.

Results

The here presented data prove that both the temperature and the hydraulic conductivity of the Rotliegend Reservoir System of the northern Upper Rhine Graben are high enough to allow geothermal exploitation at economically feasible conditions. Assuming paleo weathering zones both at the top and the bottom of the reservoir with a higher degree of degradation and segmentation of the rock mass, zones of even higher hydraulic conductivities can be expected increasing the potential production rates. Another primary target for geothermal explorations are the major fault systems of the Upper Rhine Graben where a higher degree of fracturing will most likely further increase rock mass permeability.

Furthermore, the comparison of poroperm data with the different standard equations for permeability estimation shows that the permeability-porosity relationships based on fractal pore-space geometry by Pape et al. (1999) fits very well to the our measured data. Therefore, these equations can be used for permeability prediction at reservoir depth and if sufficient geophysical borehole-log data are available, permeability can be calculated directly applying the methods introduced by Pape et al. (2000).

In conclusion, detailed seismic investigations of the fault system in the reservoir remain one of the most important tools to identify zones of presumably high rock mass permeability, which are primary targets for geothermal exploration and production wells.



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