The Rotliegend Reservoir System of the Northern Upper Rhine Graben, Germany: From Outcrop Analogue Studies to Geothermal Reservoir Assessment*

Kristian Bär[1], Marita Felder[2], Annette E. Götz[1], Nicolaas Molenaar[3], and Ingo Sass[1]

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[1]TU Darmstadt, Institute of Applied Geosciences, Geothermal Science and Technology, Darmstadt, Germany (baer@geo.tu-darmstadt.de)
[2]PanTerra Geoconsultants B.V., Leiderdorp, The Netherlands
[3]Vilnius University, Department of Geology and Mineralogy, Lithuania

Abstract

In the northern part of the Upper Rhine Graben the up to 2,000 m thick clastic and volcanic succession of Rotliegend deposits is known to be at depths of 1,000 to 3,000 m, and thus expected to have temperatures of more than 100 °C - sufficient for hydrothermal utilization. Based on petrography and thermophysical rock properties of representative lithotypes and the integration of hydraulic test data, the heat in place and the potential of hydrothermal power generation is calculated including the distinct degree of efficiency, which led to 683 TWh. In comparison to the potential calculated for the Buntsandstein (508 TWh) and Muschelkalk (67 TWh) deposits of the southern Upper Rhine Graben, the data presented here from the Rotliegend of the northern graben zone are very promising with respect to future efficient reservoir utilization.

Introduction

The geothermal reservoir potential of the Permocarboniferous Rotliegend sediments and volcanics of the northern Upper Rhine Graben (Germany) has been overseen in past studies. 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. Hydraulic test data from more than 150 wells drilled into Rotliegend deposits were incorporated allowing the comparison of bulk and rock permeabilities and the estimation of expected flow rates from the reservoir.

Petrography

Thin section petrography shows that porosity and permeability in all samples are 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 (Figure 1), 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 (Figure 2). 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.

At the different sample localities, which lithostratigraphically belong to the lower and upper part of the Permian Donnersberg Formation, the content of such ductile components differs, causing variations 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 (Figure 4). In sandstones from the lower part with less ductile components the interparticle pores were not completely filled by deformed lithic grains (Figure 3). 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, the 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 also have the highest measured permeability of up to 1.48E-12 m² (1499.24 mD) and the lowest thermal conductivity of only 1.36 W/(m·K) (Figure 5). 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 determines 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 permeability-porosity relationship known for shaly or “unclean“ sandstones (Figure 6).

The variation in detrital composition of the sandstone suggests 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. In the present case this could potentially be related to the presence and absence of volcanic material.

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.

Geothermal Potential Evaluation

For the management and exploitation of a geothermal reservoir, the reservoir temperature and sufficiently high production rates of geothermal fluids such as water or steam are the two most important parameters. Production rates of more than 100 m^3/h with temperatures of more than 120 °C are necessary for low enthalpy 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 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 (Figure 7 and Figure 8). Based on these data and additional published isoline maps a three-dimensional structural model of the reservoir formation incorporating an interpolated temperature model has been developed.

The results of the petrographic 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; Stollhofen, 1998) and later during the formation of the Upper Rhine Graben in the Tertiary. Thus, a well developed fracture system can be assumed (Figure 9). 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 (Figure 9 and Figure 10), thus being of less importance for geothermal reservoirs compared to hydrocarbon reservoirs.

This assumption is supported by rock mass permeabilities (Figure 10), 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. 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 than the matrix permeability. Nonetheless, both matrix and rock mass permeability range over about five orders of magnitude, reflecting their heterogeneity and illustrating the need for detailed investigations (Figure 10).

Quantification of Potential

Additionally, the deep geothermal potential of the Rotliegend Reservoir has been quantified using the volumetric approach (Eq. 1) to calculate the heat in place described by Muffler and Cataldi (1978). This approach was chosen to allow comparison to the data published by Jung et al. (2002) for the deep geothermal potentials of Germany.

$$E_{th} = c_G \cdot \rho_G \cdot V \cdot (T_G - T_S) \qquad \text{(Eq. 1)}$$

E_{th}	Heat in place [J]
c_G	Specific heat capacity [J/(kg·K)]
ρ_G	Rock density [kg/m³]
V	Reservoir volume [m³]
T_G	Reservoir temperature [°C]
T_S	Surface temperature [°C]

The resulting heat in place can then be used to determine the theoretic potential for geothermal energy production considering realistic recovery factors and degrees of efficiency of standard geothermal power plants (Organic Rankine and Kalina Cycle). In comparison to the geothermal potential calculated for the Buntsandstein (508 TWh) and Muschelkalk (67 TWh) deposits of the southern Upper Rhine Graben by Jung et al. (2002), the data presented here from the Rotliegend of the northern graben zone with 683 TWh are very promising with respect to future efficient reservoir utilization (Table 1).

Results

The data presented here 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 exploration is the major fault system 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.

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.

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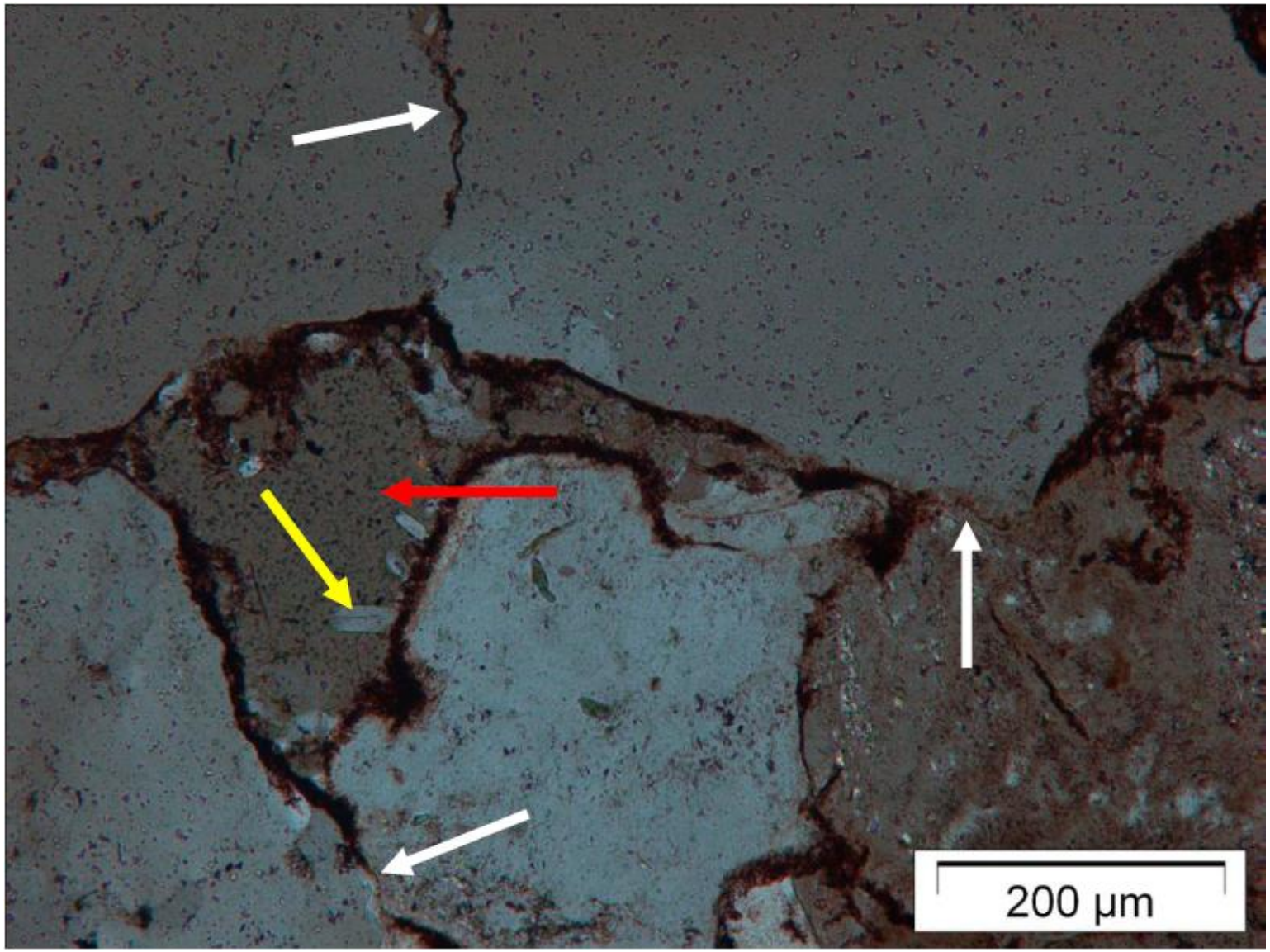

Figure 1. Sandstone of the lower part of the Donnersberg Formation (Rotliegend), which is rich in detrital feldspar and quartz. Due to the rigid grain behaviour some pore space (red arrow) was left during compaction. Close packing of the detrital grains (white arrows) reduce pore connections, which is the reason for the poor permeability. The small feldspar overgrowths (yellow arrow) in the pore do not have much effect on the porosity.

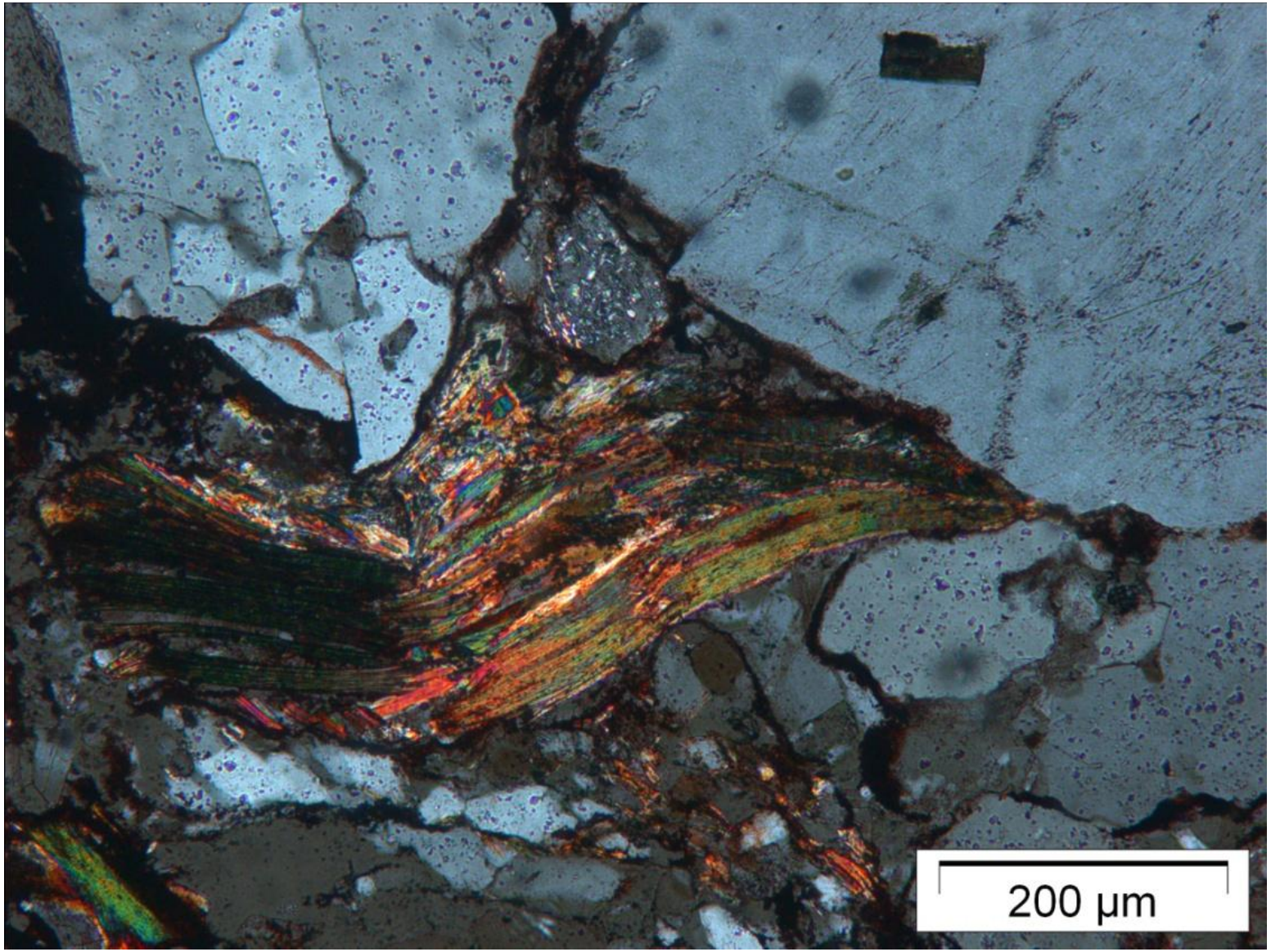

Figure 2. The sandstone sample of the lower part of the Donnersberg Formation shows a mica grain, which is deformed due to the compaction. Mica has been pressed into the former pore space. Some very small pores are visible between the rigid detrital grains, but they are disconnected.

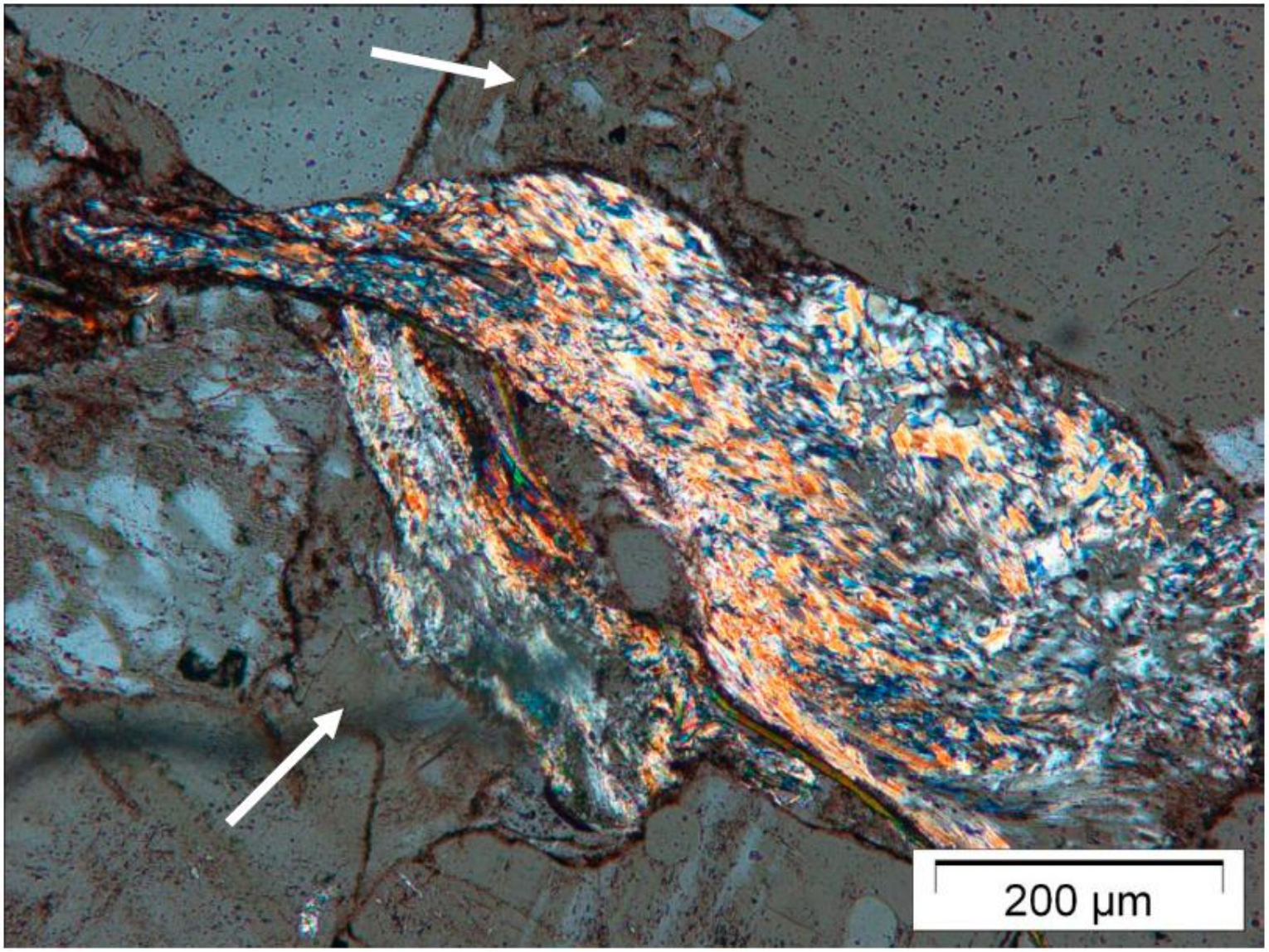

Figure 3. The two ductile lithic fragments from the sandstone of the lower part of the Donnersberg Formation are still recognizable as grains, but one of them is significantly deformed. This type of deformation is characteristic of compaction of ductile grains. Since they are the only ductile grains, surrounded by rigid grains stabilizing the grain framework, some pore space is left (white arrows).

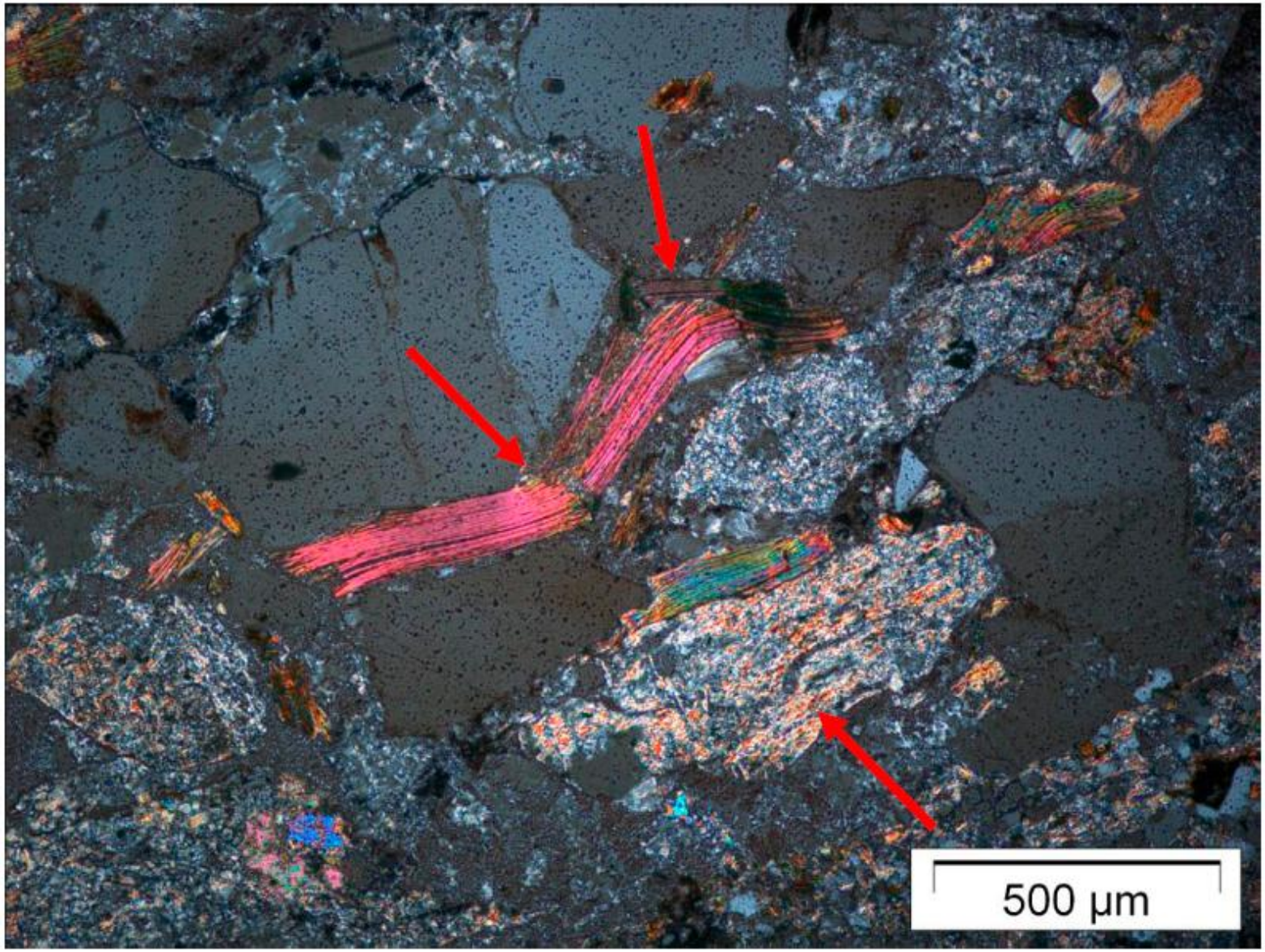

Figure 4. With mainly ductile grains in the sandstone of the upper part of the Donnersberg Formation, the deformation of the individual grains is much stronger (red arrows) and pore space has more or less completely been lost.

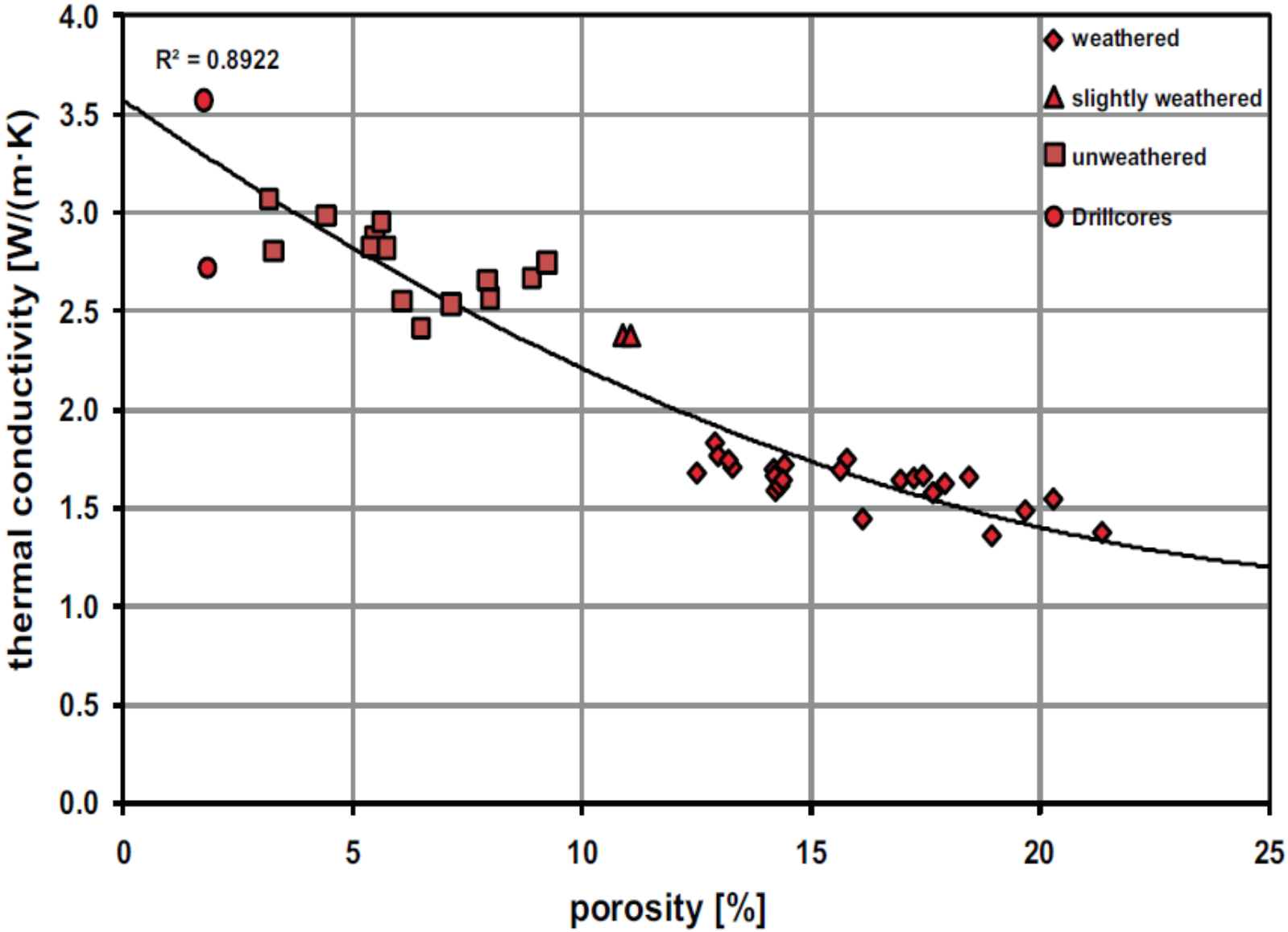

Figure 5. Thermal conductivity versus porosity plot of the poorly sorted clastic rocks of the Rotliegend of the northern Upper Rhine Graben and the adjacent graben flank outcrops, showing a clear correlation between the two parameters.

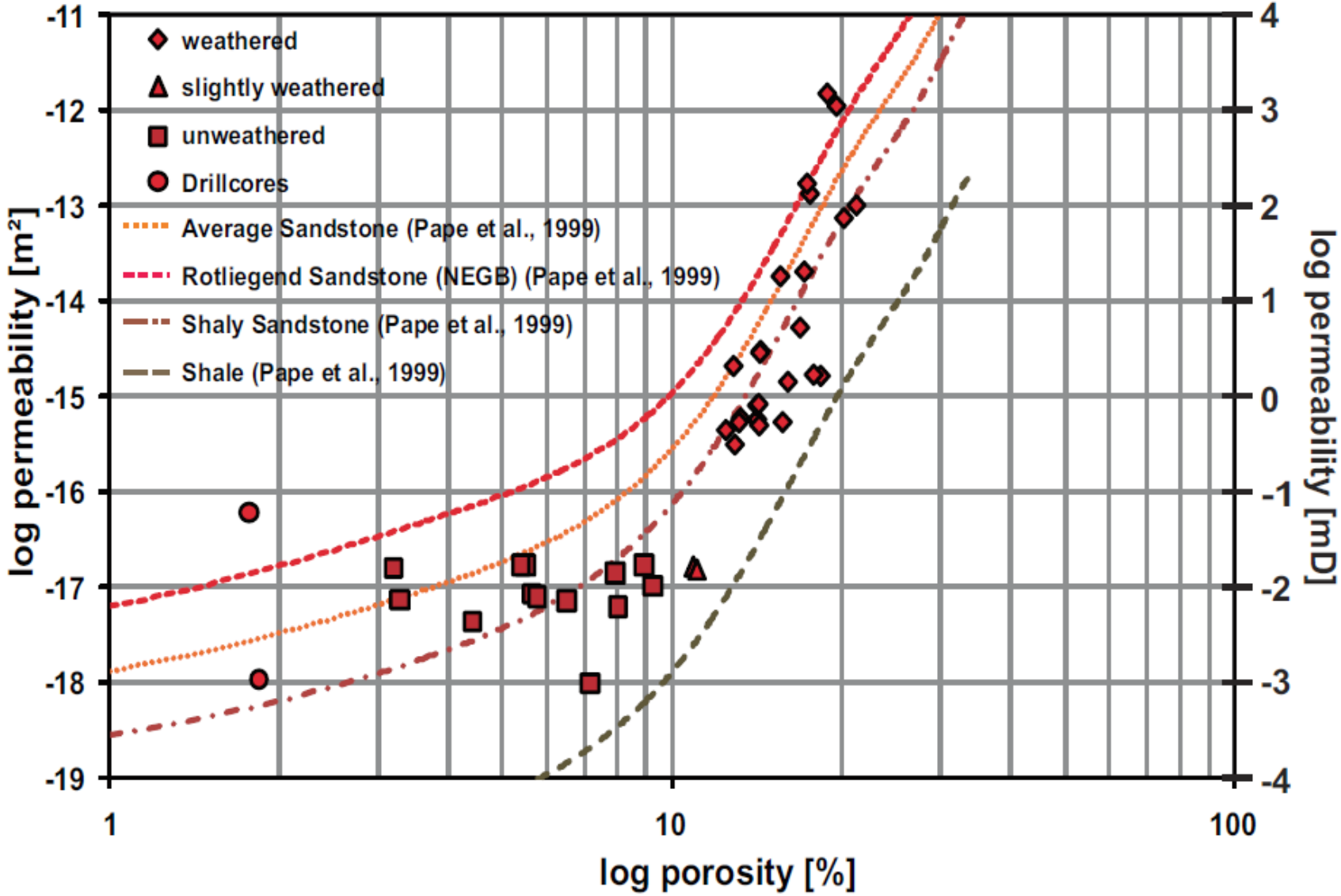

Figure 6. Log-log plot of permeability versus porosity of the same set of samples. The given lines defining permeability-porosity relationships are based on the permeability prediction equations based on fractal pore-space geometry by Pape et al. (1999) for different rock types, which were developed 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.

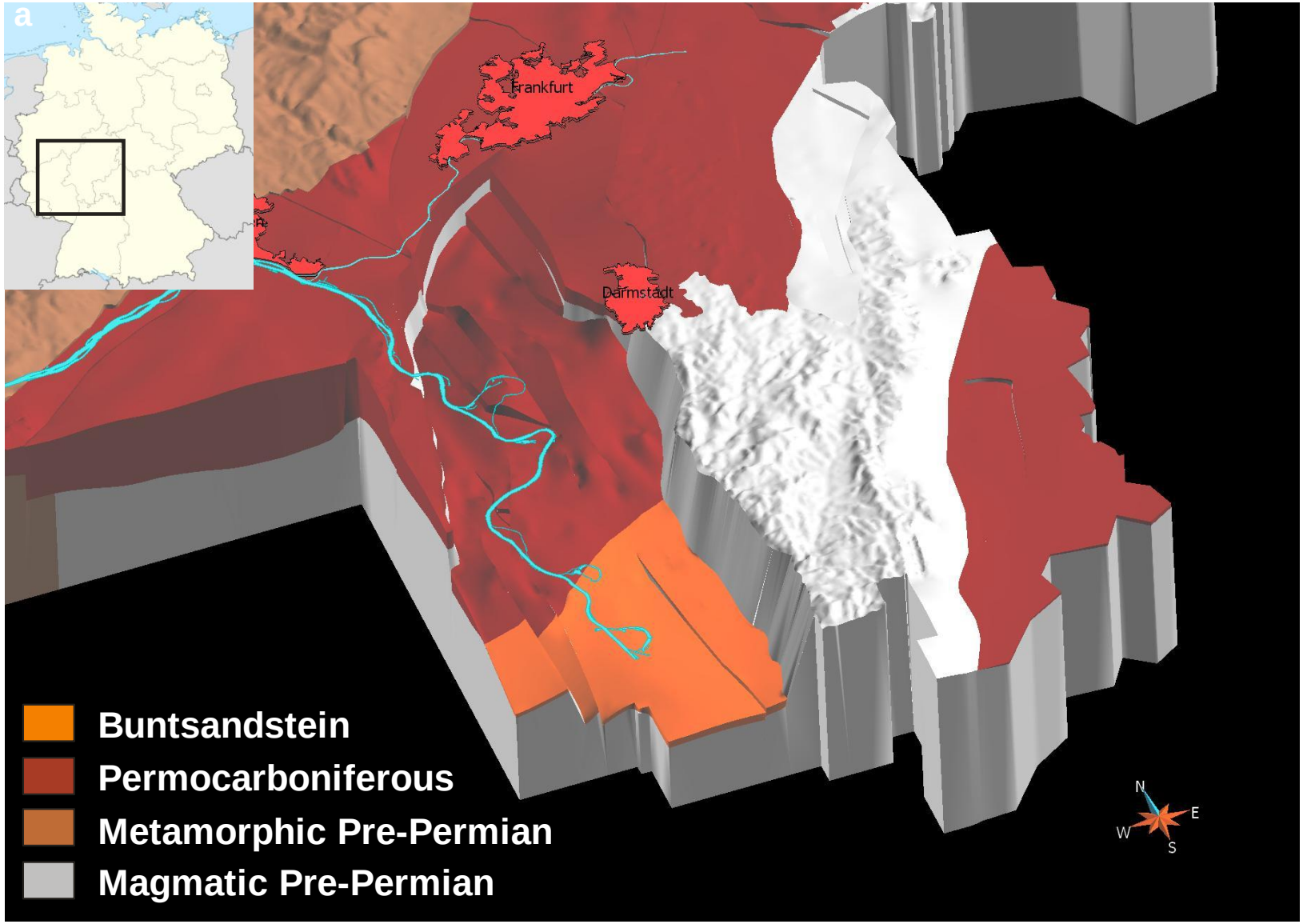

Figure 7. Section of the geological 3D model of Hesse (Germany) (Arndt et al., 2011). View from south-southwest onto the Permocarboniferous Rotliegend Reservoir System (red) of the northern Upper Rhine Graben. The Tertiary and Quaternary graben fill is not shown. The height of the model is 6 km. The view is 5 times vertically exaggerated.

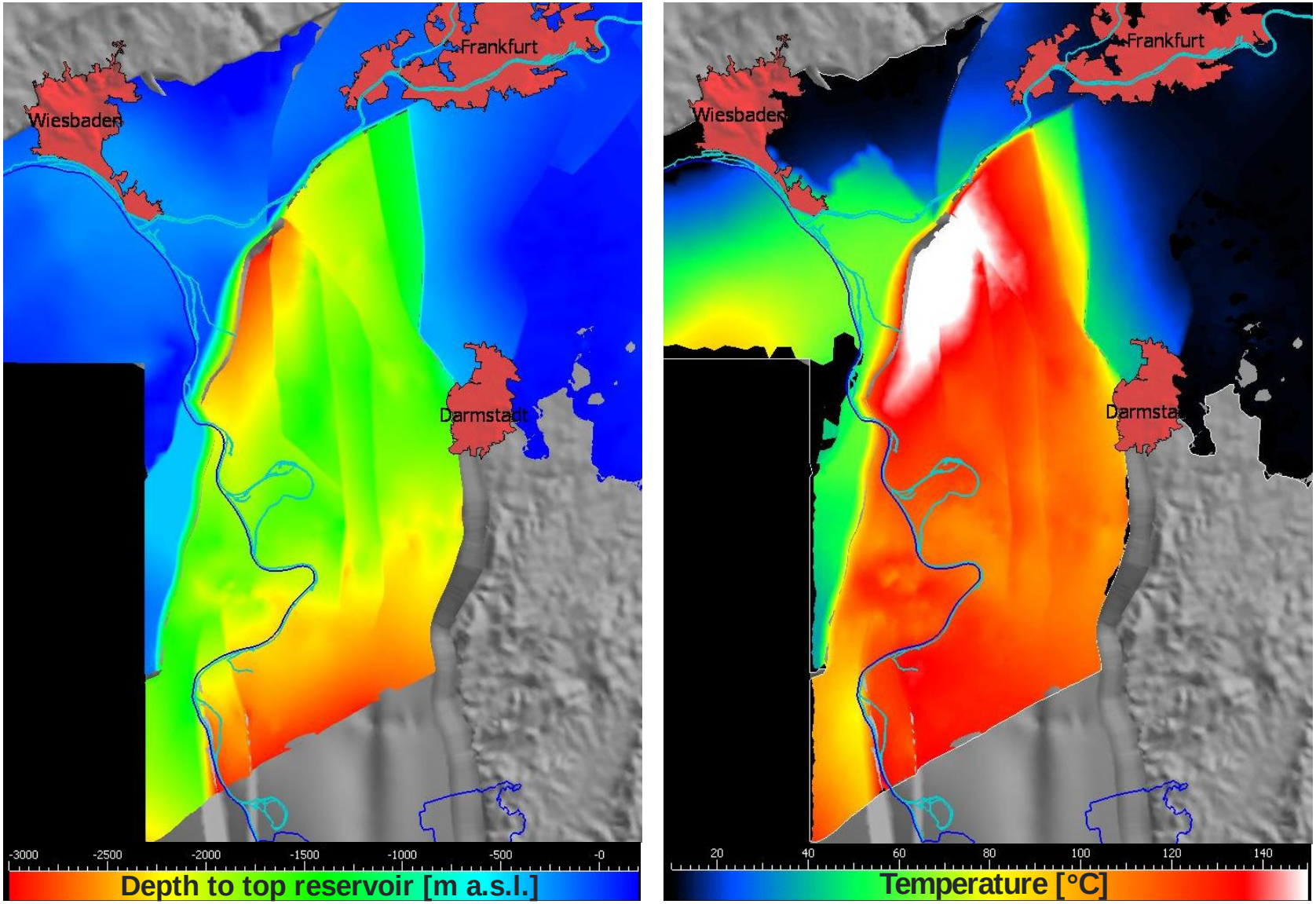

Figure 8. (left) Top view of the northern Upper Rhine Graben showing the depth of the top of the Rotliegend Reservoir System below ground level (Bär et al., 2010). Outcrops of Rotliegend rocks are located between Wiesbaden and Frankfurt and northeast of Darmstadt. (right) Top view of the northern Upper 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.

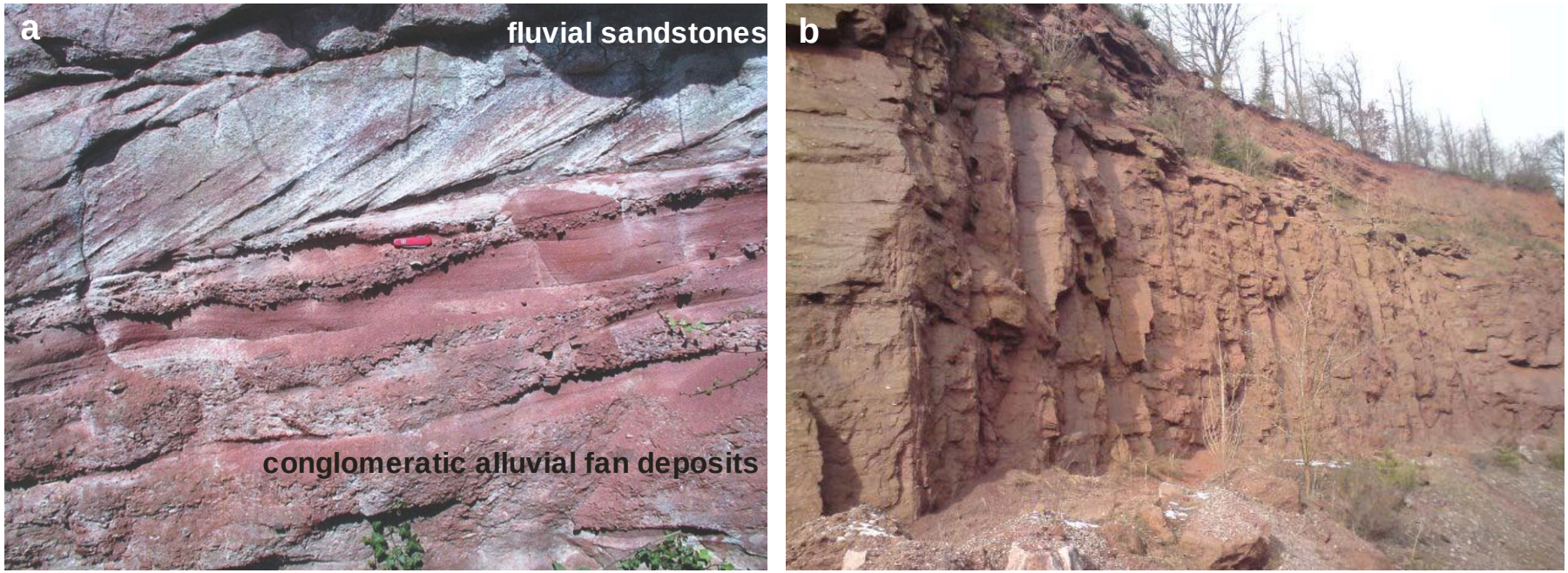

Figure 9. a) Outcrop photo of a typical Rotliegend succession showing the different facies types (1) fluvial sandstones, and (2) conglomeratic alluvial fan deposits. b) Outcrop photo of a typical Rotliegend sandstone (Gottschalk, 2010) illustrating the system of fractures, fissures and bedding planes dominating the rock mass permeability which result in higher hydraulic conductivity than expected by only considering the matrix permeability.

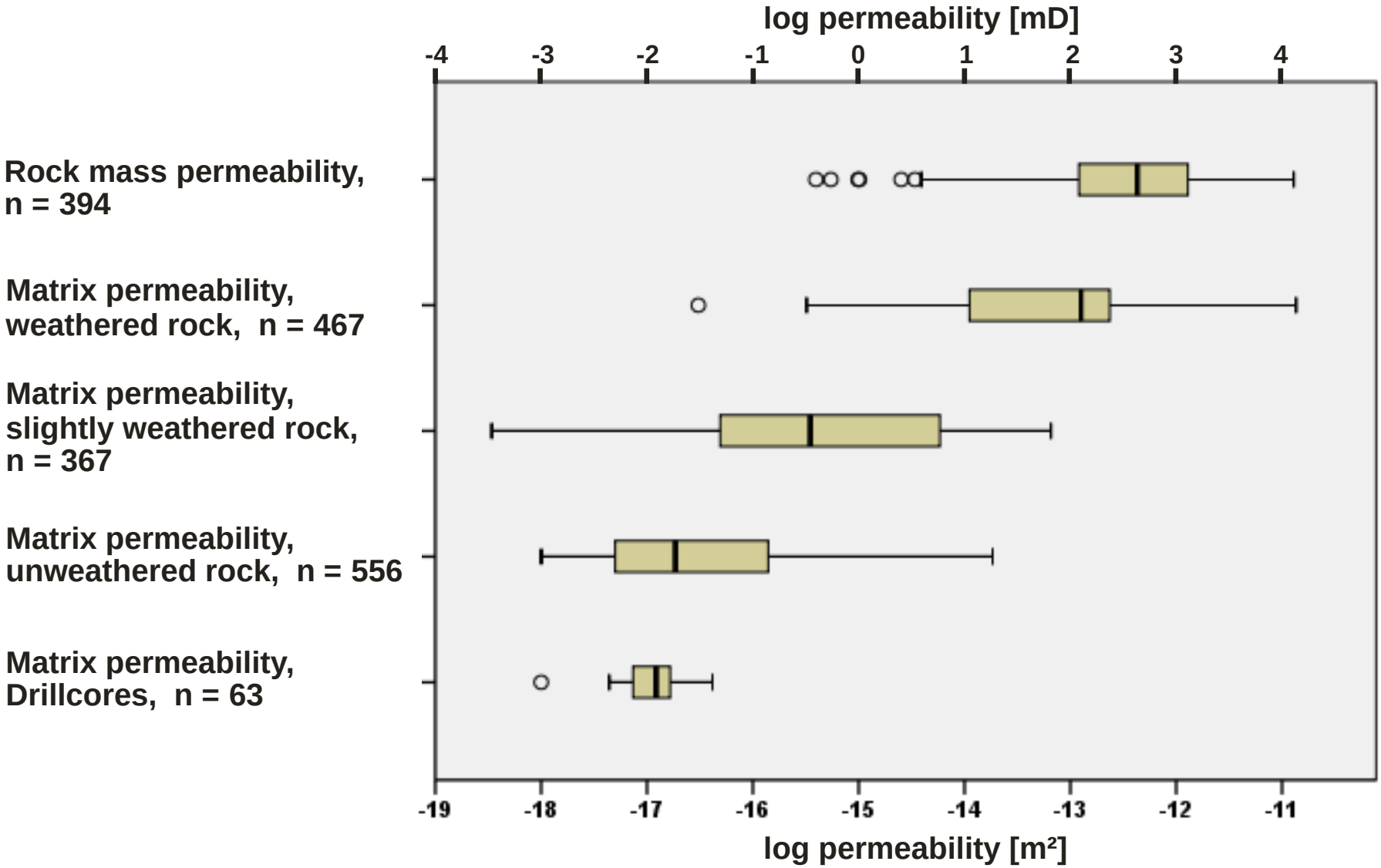

Figure 10. Box-whisker-plots of rock mass and matrix permeabilities of the Rotliegend Reservoir System of the northern Upper Rhine Graben and adjacent regions. Rock mass permeabilities were determined through the analysis of hydraulic test data of more than 300 water wells with depths of more than 50 m. Matrix permeabilites were measured with a gas-permeameter using both the mini- and the column-permeameter modus on samples from outcrops and drill cores of different depth intervals.

Reservoir Formation	Medium Temperature [°C]	Volume [m³]	Heat in Place [EJ]	Theoretic Potential for Electricity Generation [EJ]	Theoretic Potential for Electricity Generation [TWh]
Rotliegend (northern Upper Rhine Graben, this study)	135	4,95E11	198	2,5	683
Muschelkalk (southern Upper Rhine Graben, Jung et al. 2002)	145	0,25E11	12	0,24	67
Buntsandstein (southern Upper Rhine Graben, Jung et al. 2002)	145	3,2E11	87	1,8	508

Table 1. Geothermal Potential of reservoir formations of the Upper Rhine Graben (Germany)