

Facies and Diagenesis of Permocarboniferous Geothermal Reservoir Formations (Upper Rhine Graben, SW Germany): Impact on Thermophysical and Hydraulic Properties

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Keywords: Geothermal reservoir characterization, outcrop analogue study, Permocarboniferous, diagenesis, porosity, permeability

ABSTRACT

The Permocarboniferous is the largest hydrothermal reservoir in the northern Upper Rhine Graben in SW Germany and has so far been investigated in large scale studies only. The eastern part of the Permocarboniferous Saar Nahe Basin, a variscan intramontane molasse basin, is crossed by the northern end of the Cenozoic Upper Rhine Graben. Due to the subsidence in this graben structure the top of the up to 2 km thick Permocarboniferous is located at a depth of 1 to 3 km and is overlain by Tertiary and Quaternary sediments. At this depth the reservoir temperatures exceed 150°C, which are sufficient for geothermal electricity generation with binary power plants.

To further assess the potential of this geothermal reservoir knowledge of thermophysical and hydraulic properties of the different lithostratigraphical units and facies types is essential. In the present study a combination of outcrop analogue studies and drill core investigations was conducted. In total 850 outcrop samples were analyzed, measuring porosity, permeability, thermal conductivity and thermal diffusivity. Furthermore 60 plugs were taken from drillings that encountered or intersected the Permocarboniferous in the northern Upper Rhine Graben at depths between 1,800 to 2,900 m. Petrographic analysis of 90 thin sections of outcrop and reservoir samples were conducted to quantify the mineral composition, sorting and rounding of grains and the kind of cementation. This enables the determination of the diagenesis type and its influence on porosity, permeability and the degree of compaction.

In early stage diagenesis the strongest influence on reservoir properties exhibits the Hematite-type. It is characterized by grain covering hematite coatings that inhibit cementation of pore space and compaction during diagenesis. In late stage diagenesis the Illit Meshwork-type and Bitumina-type illustrate CO₂ rich acidic pore water conditions which are interpreted as the result of a hydraulic contact to an underlying Carboniferous oil source rock. Under these conditions the hematite coatings are dissolved and the protection of these sandstones against cementation and compaction is eliminated. During the formation of the Upper Rhine Graben this reaction caused a strong reduction of porosity and permeability. Of the encountered facies types the eolian sandstones of the Kreuznach Formation (Upper Nahe Subgroup) exhibits the best reservoir properties. Based on the combined investigation of facies and diagenetic processes, reservoir properties of the different Permocarboniferous formations within the northern Upper Rhine Graben and their changes with burial depth and temperature can be predicted with satisfactory accuracy. This leads to a better understanding of the reservoir and enables an adapted approach for exploration and exploitation of these geothermal resources.

1. INTRODUCTION

The Permocarboniferous represents the largest hydrothermal reservoir in the northern part of the Upper Rhine Graben (URG) and has so far been investigated in large scale studies only (Haenel & Staroste 1988, 2002, Hurter and Schellschmidt, 2003; Arndt et al., 2011; Bär et al., 2011; Sass and Hoppe, 2011; Bär, 2012). At its northern end, the Cenozoic Upper Rhine Graben crosses the Permocarboniferous Saar Nahe Basin, a variscan intramontane basin, in SW Germany. In this area the top of the up to 2 km thick formation of siliciclastic, volcaniclastic and volcanic rocks is located at a depth of 1 to 3 km and covered by Tertiary and Quaternary sediments. The reservoir temperatures of the Permocarboniferous modeled by Arndt et al. (2011) and by Agemar et al. (2012, 2013) for reservoir depth in the northern URG exceed 150 °C (Fig. 1). Thus the electricity generation with binary geothermal power plants is feasible. The Permocarboniferous deposits consist of different lithofacies types including fine-, middle- and coarse-grained sandstones, siltstones, volcanics and subsidiary volcaniclastics and carbonates (Schäfer 2005). The coarse-grained sandstones are considered to have the best rock matrix properties. In terms of fluid transport, bulk rock permeabilities along faults and in associated damage zones are up to two magnitudes higher than matrix permeabilities of unfractured rock (Evans et al., 1997; Lockner et al., 2000; Rawling et al., 2001; Schraft, 2005; Stober and Bucher, 2007; Stober and Jodocy, 2009). Nonetheless, favorable matrix permeabilities may contribute up to 30 % to the fluid transport in fractured reservoir rocks as described for the comparable Buntsandstein formation by Bitzer (2007). Bulk rock permeabilities of the Permocarboniferous were investigated by Bär (2012) and Aretz et al. (2013). In the present study, the matrix rock properties and their controlling factors are investigated.

Early and late stage diagenetic processes belong to the most important factors for the development of the matrix reservoir properties in siliciclastic rocks (Gaupp et al., 1993). The Hematite-type occurring in early diagenesis has the most beneficial influence on reservoir properties. It is characterized by grain covering hematite coatings that inhibit cementation of pore space and compaction during diagenesis (Houseknecht, 1987; Gaupp et al., 1993). Other early stage diagenesis types as the Sebhka- and Dolomite-types are characterized by the cementation of calcite and dolomite. Grain covering illite coatings result from the Illite Coating-type. These types all result in poor porosity and permeability characteristics. In late stage diagenesis the Illite Meshwork-type and Bitumina-type usually occur in combination with CO₂ rich acidic pore water conditions. These can occur as the result of a hydraulic contact to an underlying oil source rock (Schöner 2006), which in our case could be organic rich Carboniferous pelites. In this late stage diagenesis types the bleaching of sandstones caused by the dissolution of hematite coatings, the illite formation and the

bitumen impregnation are connected closely to each other and happen successively. The result is a reduction of porosity and permeability and a higher degree of compaction (Houseknecht, 1988; Gaupp et al., 1993; Schöner, 2006).

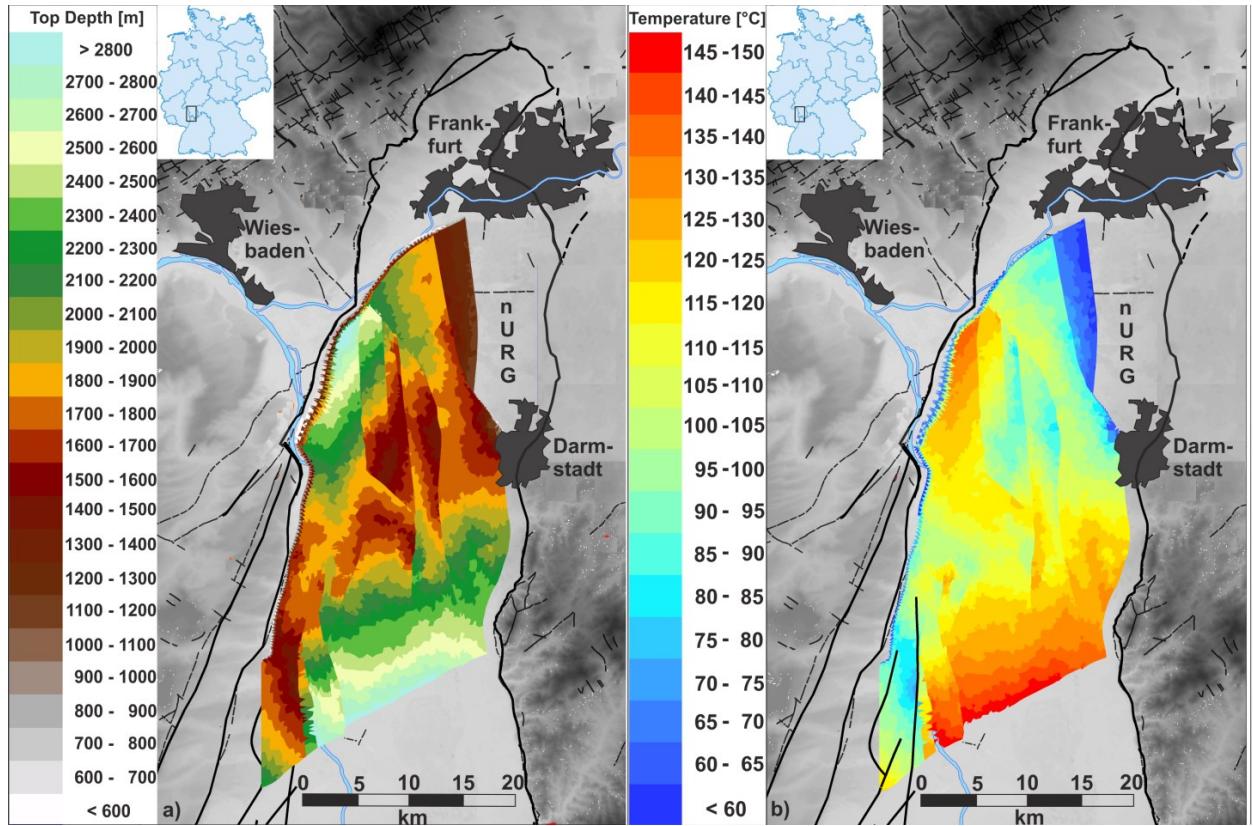


Figure 1: Depth (a) and temperature (b) of the top of the Permocarboniferous in the northern Upper Rhine Graben in SW Germany (modified after Sass and Hoppe (2011) and Bär (2012)). nURG = part of the northern Upper Rhine Graben where the top and temperature of the Permocarboniferous is not shown due to temperatures of less than 60 °C.

2. GEOLOGIC SETTING

With an extension of approximately 100 x 30 km the Saar Nahe Basin is the largest and with a cumulated sediment thickness of 8 km the deepest of about 70 intramontane basins (Hertle, 2003). They are evidence of a long-range extensional regime and have been formed due to the erosion of the Variscan orogen. With the onset of the Permocarboniferous basin fill parts of the southern source areas have been exhumed and affected an enhanced subsidence at the Hunsrück Taunus Boundary Fault (HTBF) (Ebel and Flick, 1989). The HTBF is a reactivated Variscan fault zone and marks the northern border of the Saar Nahe Basin (Müller, 1996).

During the deposition of the Kusel beds (Remigiusberg to Lauterecken formation), which form the basal units of the Permocarboniferous, meandering rivers were the dominant depositional environment (Müller, 1996; Schäfer, 2011; Fig. 2). The Altenglan Formation in the Kusel beds was deposited mainly in lacustrine environments (Schäfer, 1980). During the deposition of the Lebach beds (Jeckenbach to Disibodenberg formation) a narrowing of the Saar Nahe Basin and a higher relief of the source areas caused a change to fluvial environments with anastomosing systems (Schäfer 1980). In the Tholey beds (Oberkirchen and Thallichtenberg Formation) planation of the basin caused the system to change back to meandering fluvial style. The axis of these meander belts, which drainage areas reached far beyond the basin, was parallel to the variscan basin axis. They transported coarse-grained sediments from the Vosges close to the southern part of the URG into the basin (Schäfer, 2005). This development was connected to a tectonic reorganization of the basin. A NW-SE constriction of the variscan orogeny caused a weak folding of the basin and was accompanied by the volcanism of the Donnersberg formation. Basaltic and andesitic lava flows, tuffs and spacious pyroclastic deposits with large lateral extend were deposited (Stollhofen, 1994). These volcanic products are intercalated with coarse-grained siliciclastic deposits originating from the southern source areas Vosges, the Odenwald and the Spessart Mts. (Stollhofen, 1998). The continuing oblique subsidence at the HTBF led to the formation of conglomerate and breccia rich alluvial fans along the northern basin margin that reach into the basin for several kilometers (Wadern formation) and to the continuing shift of the depocenter towards NE (Schäfer, 1989; Marell, 1989). As a result of the depocenter shift towards the eastern end of the basin, the Sprendlinger Horst, being a horst structure already in these times, was also affected by the basin deposition (Henk 1993).

With the beginning of the Upper Nahe Subgroup the sedimentation was not controlled tectonically anymore but by thermal subsidence. As a consequence the sedimentation crossed the tectonic borders and even covered the Hunsrück and the southern source areas (Stollhofen, 1998). The dominance of eolian and fluvial depositional environments lead to the deposition of middle- to coarse grained sediments (Kreuznach and Sponheim formations). Due to a subsiding volcanism tectonic activity and a climate change towards arid conditions the basin geometry flattened and playa conditions became dominant. This led to the deposition of red siltstones and fine sandstones of the Nierstein formation at the end of the Upper Nahe Subgroup (Schwarz et al., 2011).

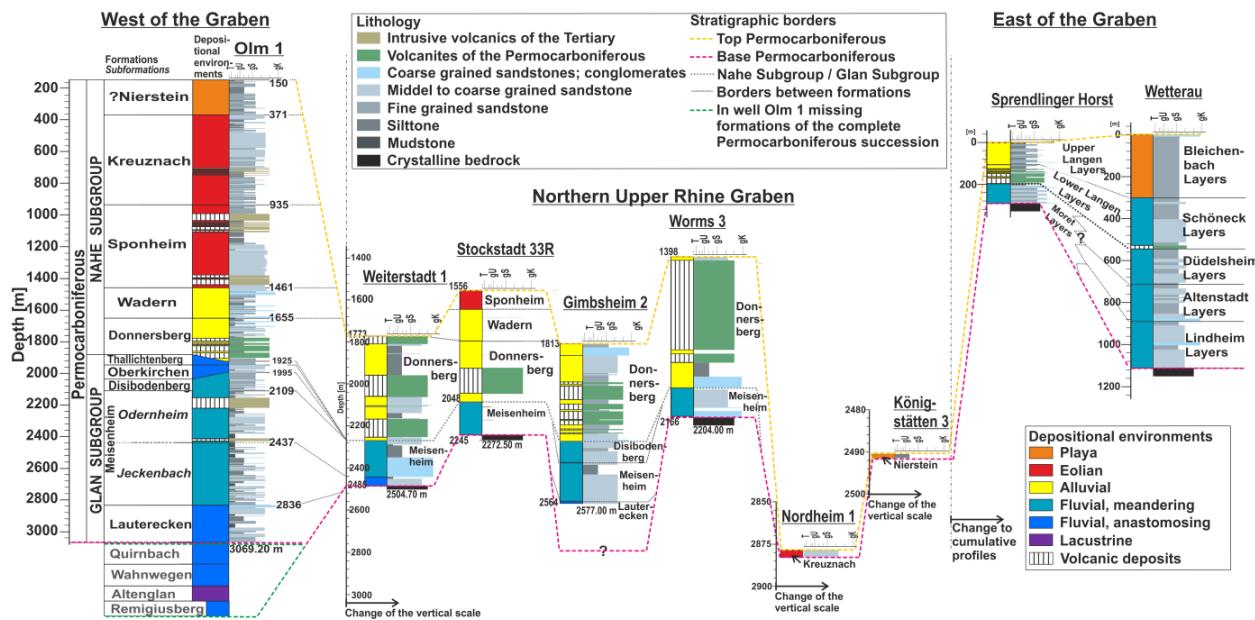


Figure 2: Correlation of the lithostratigraphic units and depositional environments based on deep exploration wells in the northern Upper Rhine Graben as well as west and east of the graben (lithostratigraphic units after Lützner et al. (2012), Saar Nahe Basin after Schäfer (2005) and Becker et al. (2012), Wetterau after Kowalczyk (2001), Sprendlinger Horst after Marell (1989) and Müller (1996)) (modified after Bär, 2012). Locations of wells are given in Fig. 3.

The primary depositional thickness of the Permocarboniferous sediments which had been eroded from the Cretaceous to the Tertiary times was studied by Henk (1992) based on the compaction stage of clay minerals. They show a linear coherence with depth by the evaluation of sonic log measurements of different drillings in the Saar Nahe Basin. The calculated overburden in the southwestern part of the basin is 1,950 m and in the northeastern part even 2,450 m. In the Mainz Basin east of the Saar Nahe Basin just 600 m overburden was eroded. Angular unconformities reveal that during the Permian, from the Buntsandstein until the Jurassic and from Eocene until the Lower Miocene erosion events took place. In the Oligocene a Transeuropean graben system developed between the Mediterranean and the North Sea (Behrmann et al., 2005; Walter and Dorn, 2007) which largest part is the 300 km long and up to 40 km wide N-S trending Upper Rhine Graben. Its subsidence led to a vertical fault throw of up to 4.5 km and resulted in an enhanced geothermal gradient by the upwelling of hot fluids from the fractured upper crust (Teichmüller and Teichmüller, 1979; Clauser and Villinger, 1990; Pribnow and Schellschmidt, 2000).

3. MATERIAL AND METHODS

Outcrop analogue studies are well established method for reservoir characterization in the hydrocarbon industry (Jahn, 2008). In our study, they have been conducted in the Saar Nahe Basin west and in the Sprendlinger Horst and in the Wetterau Basin east of the northern Upper Rhine Graben (Fig. 3). In the Saar Nahe Basin 686 rock samples were taken from 82 outcrops. Additionally one drill core with depths from 10 to 70 meters was sampled. In the Sprendlinger Horst 94 rocks samples were taken from 4 outcrops and two drill cores with depths from 0 to 55 and 65 meters were sampled. In the Wetterau 43 rock samples were taken from 5 outcrops. Additionally, 60 rock plugs were sampled from drill cores of the 6 hydrocarbon exploration wells Worms 3, Nordheim 1, Gimbshausen 2, Stockstadt 33R, Weiterstadt 1 and Königstätten 3. These wells intersected the Permocarboniferous in the northern Upper Rhine Graben from depths of 1,800 to 2,900 m (Fig. 3). Each of the 14 lithostratigraphic formations and six lithofacies types including fluvioanastomosing, fluviole meandering, lacustrine, alluvial, eolian and playa was sampled.

The rock samples were cut to cylindrical plugs with heights of 20 to 30 mm and diameters of 40 mm. They are orientated parallel and orthogonal to bedding and were oven dried at 105°C for at least 24 hours. The petrophysical parameters measured include porosity, permeability, density, thermal conductivity and thermal diffusivity. The sedimentological investigations include mineral composition, sorting and rounding of grains, the kind of cementation and the determination of diagenesis types.

The porosity was measured with a helium pycnometer and the bulk (or raw) density with a powder pycnometer. For the determination of the matrix permeability a columnar gas permeameter was used. The apparent permeability is measured at five different pressure stages from 1 and 5 bar to enable the calculation of the intrinsic permeability (Klinkenberg, 1941). The thermal conductivity and diffusivity was measured with an optical thermal scanner. The measurement is based on the optical scanning method with the use of infrared thermal sensors (Popov et al., 1999).

For petrographic analyses one thin section per sampling location was prepared. In total 55 thin sections of outcrop samples and 35 thin sections of reservoir samples were examined. The mineral composition was studied by pointcounting of at least 300 grains per sample. The interconnectivity of the pore space was determined and the kind of cement and the diagenesis types according to Gaupp (1996) were studied. Additionally porosity (intergranular volume (IGV) cf. Paxton et al. (2002) and residual porosity) was pointcounted. The influence of diagenesis types on porosity, permeability and degree of compaction was investigated after Gaupp (1996) and Houseknecht (1988). The latter play an important role to predict the influence of the diagenetic changes with depth on the different lithofacies types and their rock properties (Gaupp et al., 1993; Grötsch and Gaupp, 2011). A tool for the prognosis of

geothermal reservoir properties is the thermofacies concept of Sass and Götz (2012), according to which the permeability and the thermal conductivity being significantly responsible for the heat flow, depend to great significance on the facies type.

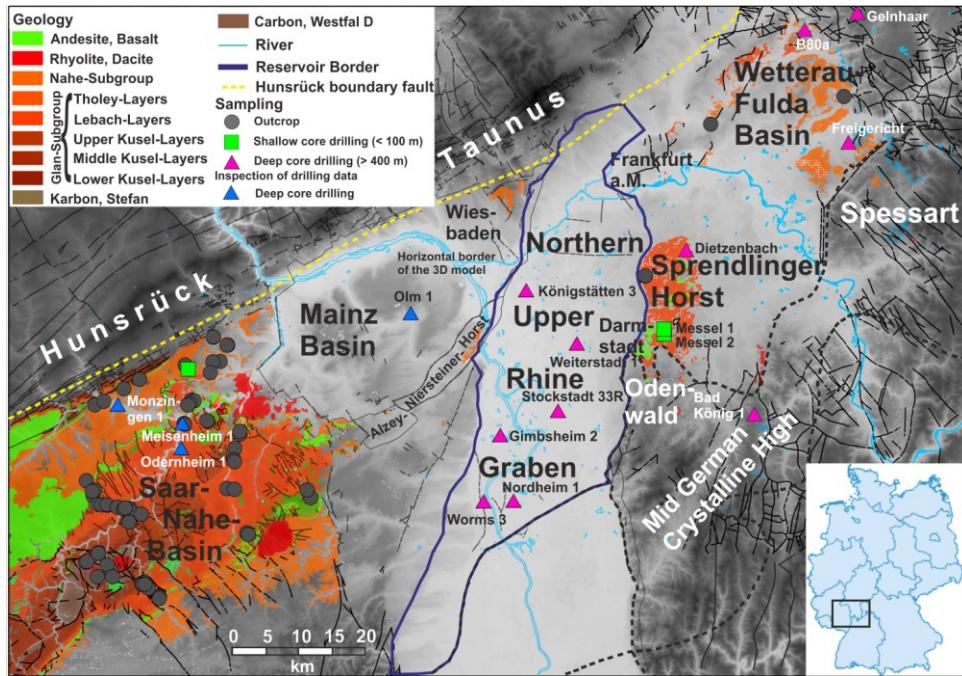


Figure 3: Geology of the Permocarboniferous in the study area west and east of the northern Upper Rhine Graben and locations of sampled outcrops, shallow and deep drill cores (GÜK 200, LGB-RLP).

The results were evaluated with respect to age and lithofacies. For a better comparison between the geothermal parameters of outcrop samples and those taken from the northern Upper Rhine Graben of depths of 1,800 to 2,900 m each set was evaluated separately in terms of the rock type, the lithofacies type, mineral composition and the diagenesis types-.

4. RESULTS

4.1 Petrophysical parameters

Among the stratigraphic units in the Glan Subgroup of the outcrop samples taken in the Saar Nahe Basin, the mean porosities and permeabilities increase continuously. The Kusel beds have a mean porosity of 10.6 % and permeability of $6.2 \cdot 10^{-17} \text{ m}^2$, the Lebach beds 14.2 % and $4.3 \cdot 10^{-16} \text{ m}^2$ and the Tholey beds 18.6 % and $1.5 \cdot 10^{-15} \text{ m}^2$ respectively (Fig. 4). The Nahe Subgroup has a mean porosity of 14.1 % and permeability of $9.9 \cdot 10^{-16} \text{ m}^2$. The mean thermal conductivities of the Glan Subgroup decrease continuously from $2.45 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ for the Kusel beds to $2.37 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ for the Lebach beds to $2.29 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ for the Tholey beds. The thermal conductivities of the deposits of the Nahe Subgroup are with $2.13 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ even less.

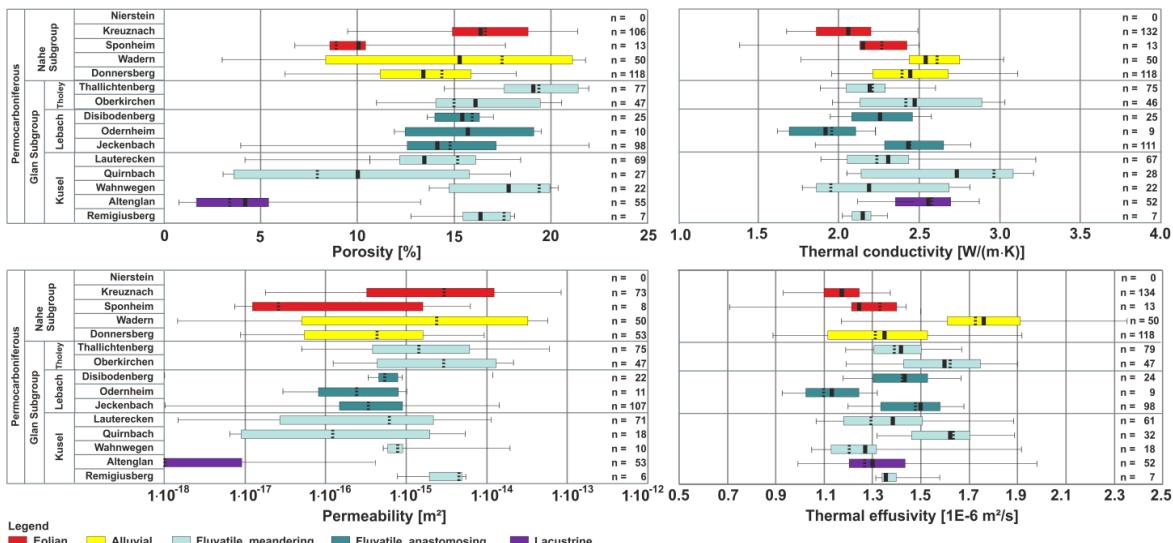


Figure 4: Porosity, permeability, thermal conductivity and thermal diffusivity box plot diagrams ordered according to the stratigraphic units of the Permocarboniferous from outcrop samples of the Saar Nahe Basin with reference to the depositional environment.

In terms of the depositional environments of sandstones taken from outcrops the eolian sandstones have the highest mean porosity with 16.4 % and highest mean permeability with $2.0 \cdot 10^{-15} \text{ m}^2$. Sandstones that were deposited in fluvial meandering systems exhibit a mean porosity of 16.1 % and with $7.6 \cdot 10^{-16} \text{ m}^2$ a lower mean permeability (Fig. 5). The lowest values were identified for the lacustrine sandstones with a mean porosity of 4.2 % and permeability of $1.0 \cdot 10^{-18} \text{ m}^2$. In terms of the reservoir rocks, the eolian sandstones also exhibit the highest porosity with 12.3 % and the highest permeability with $8.4 \cdot 10^{-16} \text{ m}^2$. Both the sandstones that have been deposited in a fluvial meandering setting and those in a fluvial anastomosing setting are characterized by low porosities of 2.7 and 2.5 % and permeabilities of $6.1 \cdot 10^{-18} \text{ m}^2$ and $3.2 \cdot 10^{-18} \text{ m}^2$, respectively. The thermal conductivities range between those of eolian sandstones with $2.06 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ and lacustrine sandstones with $2.56 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$.

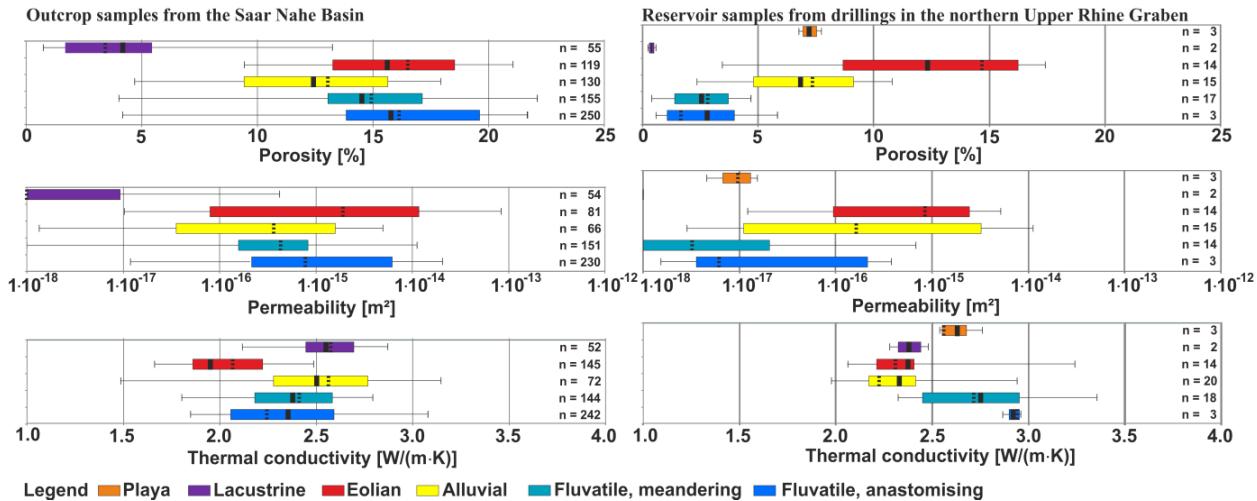


Figure 5: Porosity, permeability and thermal conductivity box plot diagrams of outcrop samples from the Saar Nahe Basin and samples of reservoir depth from the northern Upper Rhine Graben grouped according to the depositional environment.

4.2. Diagenesis

Deeply buried sandstones exhibit a wide range of diagenetic features. On the one hand they indicate which diagenetic processes already have taken place during their burial. On the other hand they allow reliable predictions for the further development of porosity and permeability during diagenesis (Gaupp 1996). At this point, it is essential to bear in mind that not only the Permocarboniferous in the northern Upper Rhine Graben has been buried at depths of at least up to 3 km. The Permocarboniferous that is exposed in the Saar Nahe Basin in present time also underwent a burial to depths of at least 1,950 to 2,450 m before being exhumed during the post Permocarboniferous tectonic development (Henk, 1992).

Textural and mineralogical features, the kind of cementation or the presence of grain coatings are important diagenetic features indicating early or late stage diagenetic processes (Gaupp 1996). Diagenetic features caused by coeval diagenetic processes can be grouped in diagenesis types. Each of them can have a major influence on the reservoir quality. The diagenesis types identified in the Permocarboniferous of the Saar Nahe Basin were grouped from early to late stage diagenesis:

- 1) Sebkha-type cementation (SB-type) indicates an early cementation of pore space mainly by anhydrite and calcite and high IGVs of up to 40 %. This type has a negative influence on porosity and permeability during burial. SB-types occur in alluvial, fluvial and eolian sandstones.
- 2) The Illit Coating type (IC-type) is characterized by illite coatings covering grain surfaces. Under presence of pressure solution they cause a reduction of the IGV resulting in porosity and permeability reduction. IC-Types are found in fluvial and lacustrine sandstones.
- 3) The Hematite type (H-type) is marked by aggregates of hematite coating grain surfaces. They inhibit cementation during further burial and therefore preserve high IGVs as well as high porosities and permeabilities even at greater depths. H-type is the only diagenesis type being present in eolian facies and was observed for the alluvial facies as well.
- 4) The Dolomite type (D-type) is characterized by the cementation of intergranular dolomite crystals. They indicate ephemeral streams and terminal fan environments. This type has a negative influence on the porosity and permeability development during subsequent diagenesis.
- 5) The Illite Meshwork type (IM-type) occurs only at late stage diagenesis and is marked by illite palates. Their presence is dependent on the availability of appropriate pore fluids that may have been provided by feldspar dissolution. Meshwork illite forms in acidic/CO₂-bearing pore waters during early stages of oil charging (Surdam et al., 1984; Gaupp et al., 1993; Cookenboo and Bustin, 1999; Barclay and Worden, 2000). Schöner (2006) postulated that the growth of fibrous illite is promoted by the impregnation of pore surfaces by hydrocarbons and therefore is most intensive when a hydraulic contact to a hydrocarbon source rock (in this study Carboniferous rocks) is available. Since the pore necks are closed by growing fibrous or meshwork illite the permeability of IM-type dominated sandstones is strongly reduced. Due to the fact that acidic pore waters can solve preformed pore cementation, the resulting secondary porosity can be relatively high in those sandstones (8 to 15 %).
- 6) The Bitumina type (B-type) characterizes faint black impregnations of pore walls. It is interpreted as former oil fill that migrated from underlying organic-rich source rocks as for example Carboniferous coal seams (Littke et al., 1996). After Worden and Morad (2003) clay reactions slow down after oil migration into a water-wet sandstone and completely stop in

an oil-wet sandstone. Therefore, the bleaching of sandstone, the illite formation and the bitumen impregnation is connected closely to each other and happen successively (Schöner 2006). B-Type dominated sandstones exhibit, similar to IM-type dominated sandstones, low permeabilities and relatively high porosities.

Table 1: Diagenesis types of sandstones of the Permocarboniferous of the Saar Nahe Basin, their geological controlling factors, temporal sequence and influence on reservoir quality (Gaupp, 1996). The late stage diagenesis types are caused by organic diagenetic processes.

Diagenesis type	Short form	Temporal Sequence	Influence on Reservoir Quality Porosity Permeability	Major Geological Controlling Factors
Sebhka-Type	SB	early	--- --	Early precipitation of calcite in unsaturated vadose zone
Illit coating-Type	IC	early	-- --	Infiltration of detrital clay forming clay coats
Hematite-Type	H	early	++ +++	Fe-Oxide pigmentation of grain surfaces by fluctuating groundwater levels
Dolomite-Type	D	early	- -	Early cementation by groundwaters with low sulfate contents
Illit Meshwork	IM	late	+ ---	Illit growth in acidic fluids caused by hydraulic contact zu oil source rocks
Bitumina-Type	B	late	+ -	Impregnation by bituminous matter as relics of former oil fill or traces of migration

For iron oxide reduction and bleaching of red beds liquid hydrocarbons are considered to be the most reducing agents (Parry et al., 2004; Garden et al., 2001; Schöner, 2006). Bleaching of red beds often occurs close to faults and fractured zones that have acted as conduits for the transport of acidic fluids (Foxford et al., 1996; Beitler et al., 2003; Schöner, 2006). There are a number of possible processes that can lead to the reduction of hematite in CO₂-contaminated pore waters. First hematite can be reduced to pyrite from sulfur bearing oils:



Iron reduction may also take place where CH₂O is used for a hydrocarbon compound:

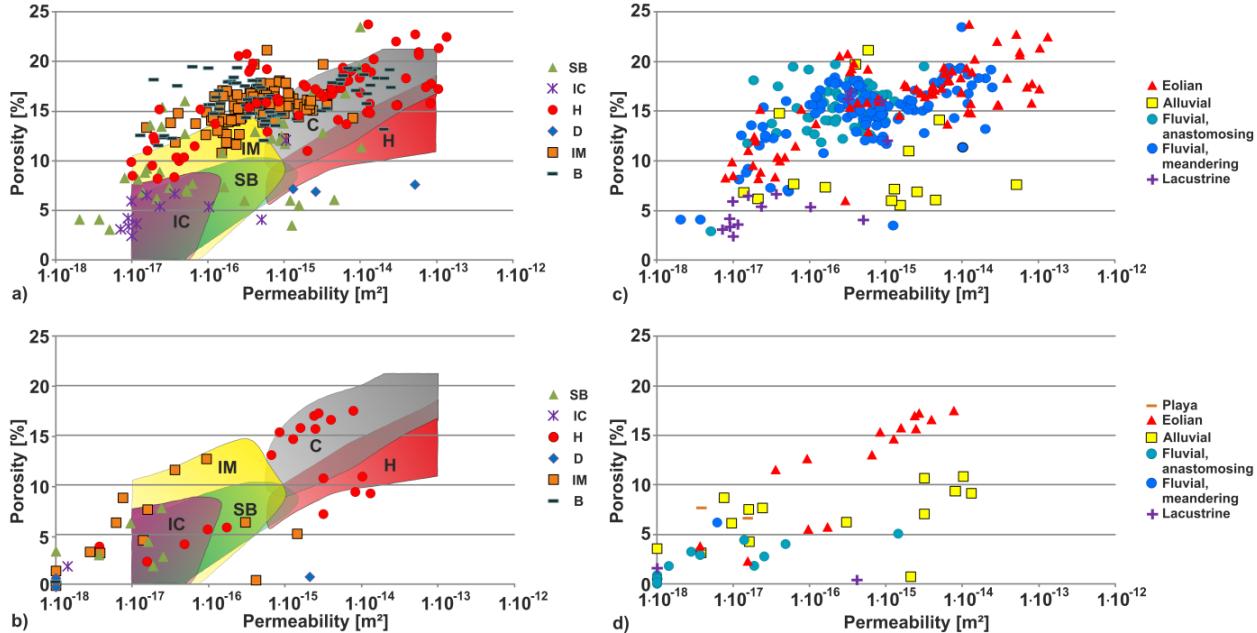
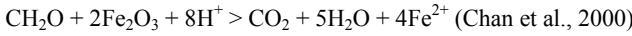


Figure 6: Permeability-porosity-plots grouped according to a) diagenesis types of outcrop samples, b) diagenesis types of reservoir samples correlated with diagenesis type fields after Gaupp (1996), c) depositional environments of outcrop samples and d) depositional environments of reservoir samples.

The permeability-porosity plot of the dominant diagenesis types of outcrop samples taken in the Saar Nahe Basin illustrates low porosities and permeabilities of SB-type sandstones (9.5 %; $6.2 \cdot 10^{-17} \text{ m}^2$, n = 49), of IC-type sandstones (5.3 %; $1.3 \cdot 10^{-17} \text{ m}^2$, n = 13). For the D-type sandstones low porosities and high permeabilities were observed (7.2 %; $2.6 \cdot 10^{-15} \text{ m}^2$, n = 3). The H-type sandstones show a linear trend of porosity with permeability (16.3 %; $3.2 \cdot 10^{-15} \text{ m}^2$, n = 108). IM-type sandstones and B-type sandstones show similar mean porosity and permeability values of 15.5 %, $4.1 \cdot 10^{-16} \text{ m}^2$ (n = 117) and 16.5 %, $5.4 \cdot 10^{-16} \text{ m}^2$ (n = 83) respectively (Fig. 6). The permeability-porosity plot of the dominant diagenesis types of reservoir samples exhibit low porosities and permeabilities of SB-Type sandstones (4.6 %; $1.7 \cdot 10^{-17} \text{ m}^2$, n = 8), IC-Type sandstones (1.8 %; $1.4 \cdot 10^{-18} \text{ m}^2$, n = 1), D-Type

sandstones (0.6 %; $1 \cdot 10^{-18} \text{ m}^2$, n = 5), IM-Type sandstones (5.3 %; $1.5 \cdot 10^{-17} \text{ m}^2$, n = 14) and B-Type sandstones (0.6 %; $1.0 \cdot 10^{-18} \text{ m}^2$, n = 1). The H-type sandstones are the only ones showing considerably higher values and a linear trend of porosity with permeability (12.3 %; $2.5 \cdot 10^{-15} \text{ m}^2$; n = 16).

A key finding of our investigations is that both the outcrop and the reservoir samples exhibit the same diagenesis types in the same stratigraphic units. That proves in general the applicability of outcrop analogue studies for reservoir characterization for our case study. The Glan Subgroup is characterized by B- and IM-sandstones. Despite the absence of B-type sandstones the Donnersberg formation exhibits a wide variation with IM-, SB-, D and H-type sandstones. While SB- and H-type sandstones are found in the Wadern formation, the H-type diagenesis type is dominant in the Sponheim, Kreuznach and Nierstein formations.

4.3 Compaction

The degree of compaction of sandstones which strongly influences their porosity and permeability can be quantified by the intergranular volume (IGV) (Houseknecht, 1987; Houseknecht, 1988; Paxton et al., 2002). The IGV is the sum of the intergranular porosity and cements in the former pore space. The mechanical compaction caused by lithostatic overburden pressures during burial leads to the reorientation and repacking of grains and to the reduction of the bulk volume which is characterized entirely by the reduction of the IGV (Houseknecht 1987). The reduction of the IGV caused by mechanical compaction from the initial 40 % of loose sand is limited to 26 % characterizing the arrangement of an ideal sphere packing. The IGV can be further reduced only by chemical compaction (grain dissolution) of framework grains at point contacts. This is characterized by intergranular pressure solution and indicates deeper burial depths. The IGV of the outcrop sandstones of the Saar Nahe Basin ranges from 8 to 39 % and of the reservoir sandstones from 4 to 40 %, which can be considered as the same range if the sample numbers are taken into account.

In terms of the outcrop samples the H-type sandstones exhibit the highest IGVs between 26 and 39 % and count pointed porosities between 5 and 19 %, followed by the B-type sandstones with IGVs of 12 to 30 % and porosities of 8 to 24 % (Fig. 7). The IM-type sandstones display lower IGVs of 17 to 26 % and lower porosities of 3 to 10 %. The SB-type sandstones are characterized by IGVs between 8 and 34 % and low porosities of up to 6 %. Similar low porosities were observed for the D-type and IC-type sandstones. In case of the reservoir samples the H-type sandstones also have the highest IGVs between 20 and 40 % and the highest porosities of up to 25 %. All other samples with other diagenesis types are characterized by porosities below 2 %, while the SB-type, D-type and Q-type sandstones display slightly higher IGVs than the IM-type, IC-type and B-type sandstones.

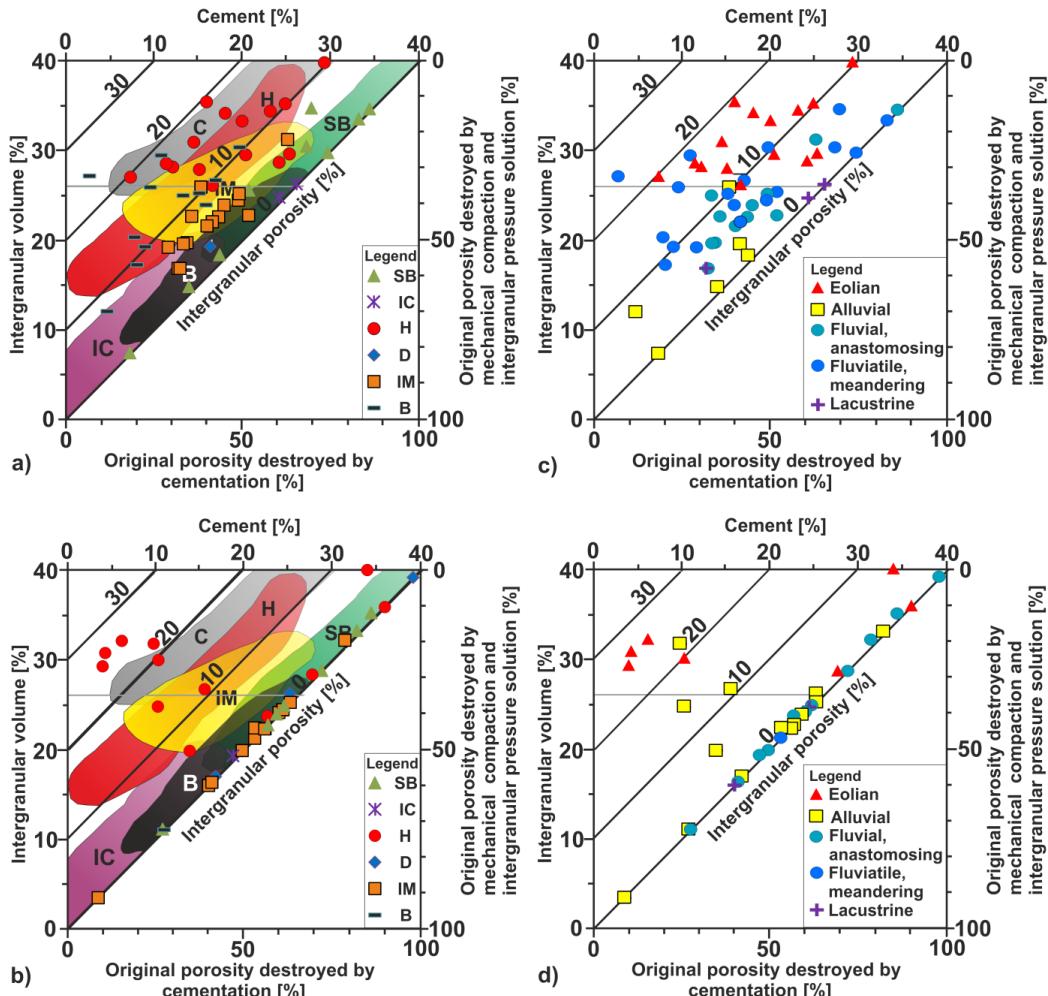


Figure 7: Compaction diagram after Houseknecht (1988) of a) diagenesis types of outcrop samples and b) diagenesis types of reservoir samples correlated with diagenesis type fields after Gaupp (1996) , c) grouped according to depositional environments of outcrop samples and d) grouped according to depositional environments of reservoir samples.

4.4 Petrography

The outcrop sandstones are classified following the nomenclature of McBride (1963) as lithic subarkose ($Q_{63} F_{19} L_{18}$, $n = 23$), lithic arkose ($Q_{54} F_{30} L_{16}$, $n = 13$), feldspar rich litharenit ($Q_{47} F_{14} L_{39}$, $n = 8$), litharenite ($Q_{17} F_6 L_{76}$, $n = 5$) and arkose ($Q_{56} F_{35} L_9$, $n = 4$), sublitharenit ($Q_{73} L_8 F_{18}$, $n = 1$) and subarkose ($Q_{70} F_{24}$ and L_6 , $n = 1$; Fig. 8).

While the sublitharenit sandstones have the lowest porosities (7.3 %) and the lowest permeabilities ($5.5 \cdot 10^{-18} \text{ m}^2$), lithic subarkoses show the highest porosities (16.2 %). Arkose sandstones are characterized by the highest permeabilities ($7.9 \cdot 10^{-15} \text{ m}^2$). Subarkosic sandstones show the highest thermal conductivities ($2.7 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$), litharenitic sandstones have the lowest with $1.9 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$.

Considering the mineral composition in terms of the different facies types the feldspar content of the fluviatile meandering sandstones ($Q_{59} F_{24} L_{17}$, $n = 16$), the fluviatile anastomosing sandstones ($Q_{57} F_{26} L_{17}$, $n = 14$) and the lacustrine sandstones ($Q_{60} F_{24} L_{16}$, $n = 3$) is higher than of the alluvial sandstones ($Q_{31} F_{17} L_{52}$, $n = 5$) and the eolian sandstones ($Q_{51} F_{14} L_{35}$, $n = 16$).

5. DISCUSSION

If a hydraulic contact to an underlying oil source rock exists in late stage diagenesis the reservoir fluids change to more CO_2 /acidic conditions (Schöner, 2006). They dissolve the hematite coatings that act as a protection against compaction and cementation. During the subsidence of the Cenozoic Upper Rhine Graben sandstones of those stratigraphic units being contaminated by CO_2 rich waters exhibit a huge loss of porosity and permeability. In contrast to the outcrop sandstones of the Saar Nahe Basin where IM- and B-type sandstones occur equally, the ratio of IM- to B-type sandstones in the reservoir amounts to 9:1. Three IM-type sandstones from drill cores of Worms 3 at the southern basin margin even exhibit thin hematite coatings. That leads to the assumption that the fluids of the today's reservoir during the deposition of the Glan Subgroup were water wet with an acidic signal and enhanced with CO_2 . But the concentration was too weak to solve the hematite coatings in some cases. Müller (1996) and Marell (1989) confirm that the propagation of oil source rocks bearing Carboniferous deposits ended approximately at the western boundary fault of the Upper Rhine Graben. That leads to the suggestion that in the area of Upper Rhine Graben oil migration into the reservoir sandstones of the Glan Subgroup did not occur everywhere but only locally in the western regions.

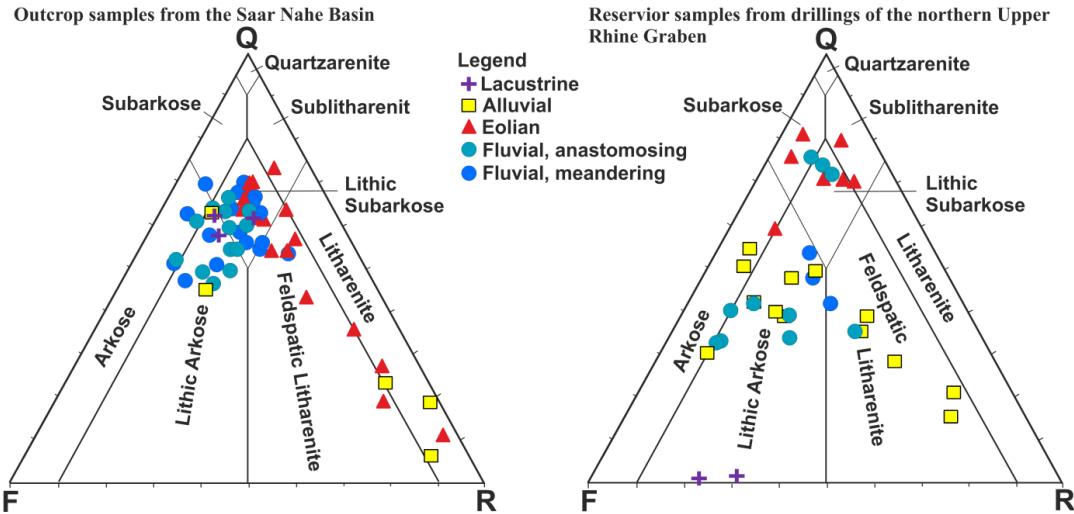


Figure 8: QFR-Diagrams (after McBride, 1963) of outcrop and reservoir samples grouped according to depositional environments, Q = Quartz, F = Feldspar, R = Lithics.

High porosities of up to 26 % of H-type diagenesis reservoir sandstones that were buried to depths of at least 2,900 m suggest that early stage diagenetic processes are the second key parameter for reservoir quality. All other reservoir sandstones with other diagenesis types exhibit porosities of less than 2 %.

The observation that the diagenesis types of outcrop and reservoir samples of different stratigraphic units of the Permocarboniferous are the same and the distribution of diagenesis types among stratigraphic units both suggest a change in pore water fluid chemistry from the base to the top of the succession. B- and IM-type sandstones characterize CO_2 -rich pore fluids during the deposition of the Glan Subgroup. The Donnersberg Formation contains a variety of different diagenesis types illustrating a mixture of weak acidic to alkaline conditions. In contrast the overlying Wadern, Sponheim, Kreuznach and Nierstein formations are dominated by the H-type sandstones pointing to alkaline pore water conditions. This leads to the assumption that the primary diagenetic features of the stratigraphic units of the Permocarboniferous have the most important influence on reservoir quality and were not caused by the Eocene subsidence of the Upper Rhine Graben and a secondary diagenesis. One possible reason for the fluid chemistry change and the decrease of CO_2 -rich pore waters from base to top could be the large vertical distance to the underlying Carboniferous oil source rocks. Another are the thick volcanic deposits in the Donnersberg Formation that could have acted as a barrier for migrating CO_2 -rich pore fluids. Furthermore the end of the syn-rift phase at the transition of the Donnersberg and Wadern to Sponheim formations (Henk, 1992) coinciding with a change from rather humid to arid climate could cause the changing conditions.

The petrography of sandstones is another important parameter for reservoir prognosis. Since during diagenesis clay mineral reactions and feldspar dissolution take place and ductile lithic fragments are easily deformed mechanically and strongly reduce the

IGV, quartz-rich, mature sandstones are less vulnerable against diagenetic processes (Pettijohn et al., 1987). The quartz-rich sandstones in the outcrop area (70 %) and in the reservoir (79 %) have granitic source rocks that exhibit good rounding and sorting features. However, in the reservoir alluvial sandstones show relative high porosities (7.3 %) and a comparably high amount of lithic fragments. This illustrates that the kind of cementation is a more important factor than the mineral composition. Nevertheless, porosity differences between eolian sandstones that have quartz contents of up to 79 % and alluvial sandstones with quartz contents of 37 % show that the mineral composition still plays a significant role. The most important factors influencing reservoir properties of buried sandstones are the existence of a hydraulic contact to an underlying oil source rock during late diagenesis, the depositional environment influencing early diagenetic processes and the mineral composition that is controlled by the kind of source rock and area.

6. CONCLUSIONS

The main conclusions of this study are:

1. The strongest and most destructive influence on reservoir quality was observed for late organic diagenetic processes. The entire Glan Subgroup is dominated by IM- and B- type sandstones. They characterize water to oil wet conditions and contact with acidic fluids that supposedly migrated from underlying Carboniferous petroleum source rocks. Under these conditions the grain covering hematite coatings were dissolved and the protection against cementation and compaction was eliminated. This caused a porosity and permeability reduction during the subsidence of the Upper Rhine Graben.
2. As second important influence on reservoir quality the depositional environments and their influence on early diagenetic processes were identified. Especially for eolian sandstones it is typical that the H-type act as protection against compaction during burial and preserves the original porosity even at greater depths. H-type sandstones frequently occur in the Wadern, Sponheim, Kreuznach and Nierstein formations of the Nahe Subgroup.
3. A third important influence is the mineral composition, maturity and grain size of sandstones that are controlled by the type of source rocks and the transport distance. Sandstones with the highest quartz contents and middle to coarse grain sizes derive from granitic source rocks of the Odenwald or Spessart which feldspar and mica content was reduced during transport.

Only if these three conditions are fulfilled, whose importance is contrary to their timing, good matrix reservoir qualities can be expected. The best reservoir qualities were identified for the thick sandstone layers of the Kreuznach formation in the Nahe Subgroup. They should be a main target in future geothermal exploration of the Permocarboniferous of the northern Upper Rhine Graben.

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