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Assessment of the Reservoir Potential of Devonian Carbonates in the Rhine-Ruhr Area, Germany

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ABSTRACT

Devonian carbonates in the Rhine-Ruhr area potentially depict reservoir formations for deep geothermal applications. Their thickness of up to 1,300 m and expected depth of > 4,400 m underneath the overlaying sediments in the study area provide suitable circumstances. The Devonian carbonates in the underground of the Rhine-Ruhr area are still widely unexplored. Besides their depth, the reason is the scarcity of hydrocarbon exploration activities in the past resulting in a lack of seismic and borehole data or core sample material. Therefore an outcrop analogue study is carried out as a first step for evaluating the reservoir potential. In the course of the project, field and laboratory data is collected and the findings will be extrapolated to reservoir conditions in the later stages. As the relevant formations crop out along the northern flank of the Remscheid-Altena Anticline, three carbonate quarries along this range were chosen for field measurements and sampling purposes: Wuppertal, Hagen-Hohenlimburg and Hönne-Valley. The most important field observations are macroscopic facies determinations for being able to make facies-related statements about the reservoir potential of different sub-formations within the Devonian carbonates and the scanline surveys for analyzing spatial and facies-dependent fracture properties. In the laboratories microscopic facies determinations and petrophysical experiments are conducted focusing on thermal and hydraulic properties in the earlier stages of the project. The combination of the facies analyses in the course of the field work and in the laboratories resulted in the detection of two main depositional facies types in the studied quarries along the carbonate range. The Schwelm-facies represents the older units deposited on an outer shelf platform subjected to relatively slow, steady subsidence. Wave-resistant, relief-forming reef bodies are not existent in this facies type. This changed towards the end of the Middle Devonian. With increased subsidence, rigid reef bodies locally rose above the carbonate platform. This so called Dorp-facies represents the second main facies type and can be subdivided into fore-reef, reef-core and back-reef. Within the Dorp-facies, only fore- or back-reef sub-facies types are on hand. Epigenetic dolomitization occurred locally within the Devonian carbonate formations. Dolomitized parts are exceptionally detected in the Hagen-Hohenlimburg quarry so far. The results of the scanline survey show that the most obvious variation in fracture properties is detectable comparing dolomitized and non-dolomitized carbonates with the latter exhibiting a higher fracture density, portion of opened fractures and length of the discontinuities. Petrophysically the difference between the non-dolomitized Schwelm and Dorp-facies is less pronounced than the difference between those units and dolomitized sections, as well, especially from a hydraulic standpoint. Total and effective porosities, as well as permeabilities, are all higher in the dolomitized parts. For the thermal conductivity values representing the thermal properties, no clear-cut spatial or facies-related trend could be recognized. The comparison of the gained values with findings of outcrop analogue studies in the Munich area, where several deep geothermal applications are already in operation, offers a promising outlook regarding the reservoir potential of the Devonian carbonates in the Rhine-Ruhr area in general. Regarding the hydraulic properties, the dolomitized sections seem to hold the highest reservoir potential, while the fracture analysis points towards the calcitic units as the favorable targets for deep geothermal operations.

1. INTRODUCTION

One of Europe's largest district heating networks with a total length of 4,300 km is located in the Rhine-Ruhr area. So far it is still supplied with fossil energy – mainly waste heat from coal-fired power plants (Knutzen et al. 2015). Deep geothermal applications hold the potential to provide sustainable energy for district heating systems in urban regions, which is shown by several operations in Munich, southern Germany (Dirner and Steiner 2015). Converting the existing district heating network in the Rhine-Ruhr area from a fossil-driven heat supply towards a sustainable one by implying deep geothermal heat holds a huge environmentally beneficial potential, as the Ruhr metropolitan area is an agglomeration of 50 cities with a population of more than 5 million people living in an area of approximately 4,400 km² (Knutzen et al. 2015). The prototype area for the conversion of the district heating system in Germany is Munich, where geothermal energy already holds an important share of the city's heat supply. According to the long-term energy supply plan of the public services in Munich, heat extracted from deep geothermal reservoirs is supposed to be the lone thermal energy provider by 2040 (Wissing 2015).

For evaluating the potential and productivity of the contemplable geothermal reservoir formations in the Rhine-Ruhr area, comprehensive geoscientific analyses are required. Outcrop analogue studies have been carried out for evaluating the potential of the Jurassic Malm-carbonates in the Munich area. Hence this approach depicts the prototype for the present study, as well. Potentially suitable geothermal reservoir formations are sampled along their surface outcrops and their facies-related structural geological and petrophysical properties are examined in order to make statements about the reservoir potential of the formation itself and the single specifiable facies types within a formation. Applying certain pressure and temperature conditions or chemical fluid compositions on a laboratory scale provides the possibility of extrapolating the gained data to expected reservoir conditions in the final stages of the project work (Homuth et al. 2014).

Due to their extensive thickness of up to 1,300 m, the depth of more than 4,400 m underneath the Ruhr area and well-known karstifications of the units, the Middle to Upper Devonian carbonates have been chosen for the present study (Franke et al. 1990, Krebs 1974, Thiel 2018). Outcrops of these formations are located in the south of the Ruhr-river on the northern flank of the Remscheid-Altena Anticline and on the edges of the Velbert Anticline (Figure 1).

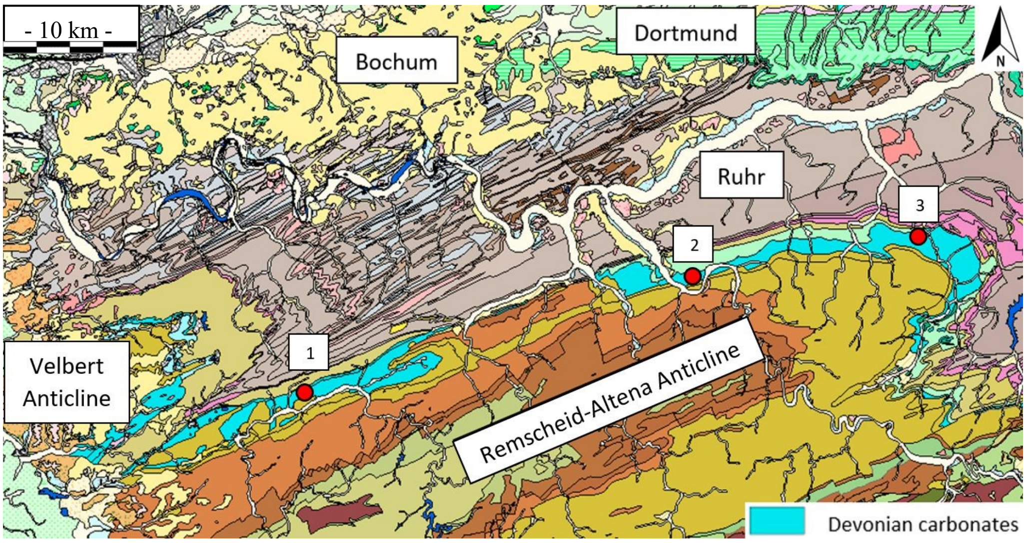

Figure 1: Map of Devonian carbonate outcrops south of the Rhine-Ruhr region. The limestone and dolomite quarries Oetelshofener lime works in Wuppertal (1), Hohenlimburger lime plant in Hagen (2) and Lhoist in the Hönne-Valley (3) are represented by the red dots (modified after Federal Agency for Cartography and Geodesy 2019).

In Figure 1 three of the carbonate quarries located in the Devonian carbonate range on the northern flank of the Remscheid-Altena Anticline, in which the field work and sample acquisition was carried out, are displayed, as well. Due to the extensive character of the analyzable outcrop sections, these pits offer perfect conditions for the structural geological field work and the macroscopic, in-situ facies determination.

2. METHODS

The present study is supposed to answer two main questions. First, if the Devonian carbonate formations of North Rhine-Westphalia exhibit proper features to serve as deep geothermal reservoir rocks. On the other hand particularly promising sub-formations like certain facies types have to be determined in order to call future studies' attention and facilitate successful drilling operations in the end.

2.1 Facies Determination

In order to be able to respond to the latter issue, the macro- and microscopic facies determination forms the first part of the project work. Facies-related variations can play a crucial role for the geothermal reservoir potential of a carbonate formation (Stober 2014). Macroscopically distinguishable outcrop sections within the three quarries are described and assigned to certain paleo-geographic settings. The most important parameters are the mineralogical composition, the fossil content and the porosity. This is also the case for the microscopic facies determination, which was carried out in the laboratory on Alizarin-Red-S stained thin sections produced with blue epoxy resin colorizing the pore space in blue. Alizarin-Red-S staining facilitates the differentiation between calcite and other minerals, since the added chemical forms Alizarin-Red-S – calcium complexes in a chelation process, if calcite is available. These complexes appear reddish, while other minerals, that did not react, stay in their original color. Post-depositional changes in mineralogy - like epigenetic dolomitization – are also taken into account, as they can have a huge impact on the reservoir potential from a petrophysical and structural-geological perspective.

2.2 Scanline Survey

In general the reservoir property evaluation of the present study consists of field work and laboratory studies. The former mainly comprises the so called scanline surveys and the macroscopic facies determination. For the scanline surveys, lines of about 5 m to 20 m are drawn on randomly chosen sections along the outcrops within the carbonate quarries. As the facies determination always depicted the first step of the field work, the facies types, in which the particular scanlines were analyzed, have always been known so that a facies-related interpretation was facilitated. For the scanline survey itself up to 16 parameters of every discontinuity of the rock formation intersecting the scanline are recorded. Those parameters mainly describe the shape, dimension, orientation and filling of the single fractures and the distance in between them (Markovaara-Koivisto and Laine 2012). Therefore, by conducting scanline analyses on outcrops representing different facies types, the fracture properties, which play a huge role for the potential of a carbonate reservoir, can be evaluated for every facies and a favorable type can be determined in the end (Lucia 2007). A representative scanline survey setup conducted in the quarry Hagen-Hohenlimburg is displayed in Figure 2. In this example different facies types are covered by the scanline. The starting and final point of the line are marked with red spray and a folding rule was placed in the picture for getting an impression of the scale. On the left side of the picture dark limestones are clearly distinguishable from light dolomites on the right hand's side of Figure 2. The two facies are separated, from left to right, by a calcite-filled fracture and another discontinuity filled with reddish debris.

2.3 Petrophysical Properties

Another part of the present study depicted the examinations in the laboratories. Every distinguishable facies type should be sampled in every location for being able to make statements about the spatial and facies-related variations of the petrophysical properties. The laboratory studies in the current stage of the project are represented by a variety of tests for evaluating hydraulic and thermal features of the Devonian carbonates. Included are facies-related permeability tests, effective and total porosity analyses and thermal conductivity measurements. By conducting a facies-related approach the most promising sub-formations can be detected. Furthermore the overall reservoir potential can be determined by comparing the petrophysical results of the present study with the ones of outcrop analogue studies examining the Upper Jurassic carbonates in the Munich area.

Figure 2: Exemplary scanline setup in the quarry Hagen-Hohenlimburg intersecting different facies types.

3. PREVIOUS STUDIES ON DEVONIAN CARBONATES IN NORTH RHINE-WESTPHALIA

The Devonian carbonates of North Rhine-Westphalia are widely unexplored, especially from a petrophysical standpoint (see chapter 3.2). In contrast to that facies classifications, which will be applied in the present study, have been carried out by various authors in the past.

3.1 Facies Types of Devonian Carbonates in Central Europe

Different facies classifications of the Devonian carbonates have been conducted in the 20th century and earlier. The most important studies are the ones of Frech (1888), Kayser (1907), Kegel (1922), Krebs (1967, 1968, 1974), Machel and Hunter (1994) and Paeckelmann (1913, 1922). Although those studies are of long standing, their classification system and nomenclature are still used. The problem of these papers is that post-depositional features, like epigenetic dolomitization or other types of recrystallization etc., are not taken into account in detail. Therefore the facies classifications only consider depositional variations.

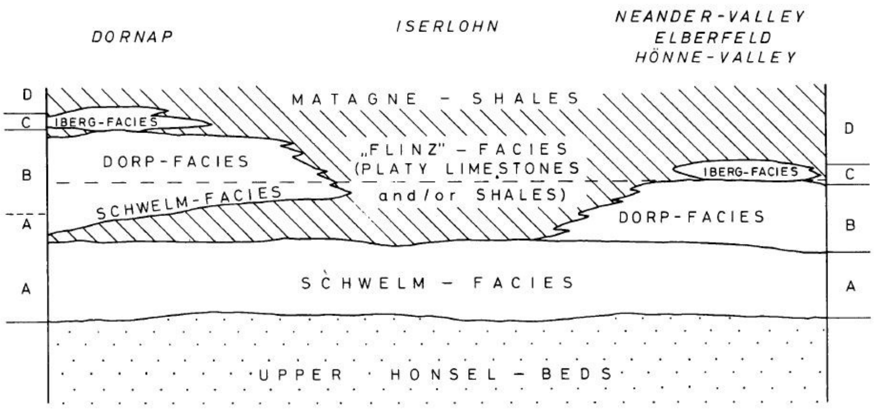

Figure 3: Facies type distribution on the northern flank of the Remscheid-Altena Anticline. The main Devonian carbonate facies are the Schwelm-, Dorp- and Iberg-facies (modified after Krebs 1967).

Figure 3 shows the main facies types along the Devonian carbonate range at the northern flank of the Remscheid-Altena Anticline displayed in Figure 1. The Upper Honsel Beds and the Flinz- and Matagne shales mainly depict under- and overlaying clastic sediments, whereas the Schwelm-, Dorp- and Iberg-facies represent the carbonate types. The Schwelm-facies always forms the Lower part within a Devonian carbonate sequence. Here, stromatoporoids and corals are not able to form wave-resistant reef structures so deposition and fossil growth occurred in a flat, biostromal environment. Therefore a sub-classification into back-reef, reef-core and fore-reef is not applicable in the Schwelm-facies, which is consequentially also called bank- or platform-facies. Furthermore the Schwelm-facies typically represents the Middle Devonian age, its matrix consists of dark, more or less bituminous, dense calcilutites and a broad variety of fossils, which are not well sorted or rounded due to the low energy environment, is available (Krebs 1967, 1974).

In contrast to that the Dorp-facies, also called reef-type 'Massenkalk', represents carbonates showing clear influences of biohermal reef buildups that formed locally (see Figure 3) during the early Upper Devonian – so during times of increased subsidence. Therefore the Dorp-facies can be subdivided into back-reef, reef-core and fore-reef. This detailed classification has also been applied in the present study. The Dorp-facies in general mostly consists of sparry rather than calcitic-micritic matrix portions and, except for the reef-core parts which only make up for a small portion of this facies type, is typically composed of more or less well rounded and sorted skeletal fragments derived from the bioherms (Krebs 1967, 1968, 1974). Machel and Hunter (1994) also sub-classified Devonian carbonates in back-reef, reef-core and fore-reef facies types taking the water energy during deposition, sorting, rounding, the texture and porosity-related features next to the fossil content and the matrix composition into account. They divided the back- and fore-reef sections into four parts depending on the distance to the reef-bodies with class I being the most distal and IV being the most proximal, while 'b' means back-reef and 'f' fore-reef, respectively. Combining the findings of the different studies was essential for the facies determination of the present study.

The Iberg-facies depicts the third main facies-type of Devonian carbonates in North Rhine-Westphalia. It consists of gray, sparry crinoid-brachiopod-limestones and represents the convex caps of the former reef-sections. The main distinguishing factor from the Dorp-facies is the absence of stromatoporoids, which are mostly replaced by tabulate corals, and the reduced thickness, which only reaches a few tens of meters. Chronologically the Iberg-facies followed after the Dorp-facies in the Upper Devonian during times of increased subsidence leading to the formation of the reef-caps underneath the zone of continuous wave action. Therefore the formation of carbonate debris stopped at that time (Krebs 1967, 1974).

3.2 Petrophysical Properties of Devonian Carbonates in North Rhine-Westphalia

As already mentioned, petrophysical data of the Devonian carbonates in the study area are quite sparse. Jorand et al. (2015) examined potential geothermal reservoir rocks in the northeastern part of the Rhenish Slate Mountains and the Lower Rhine Embayment. Out of 476 samples which were analyzed in respect of a variety of petrophysical features like density, porosity, permeability and several thermal properties, only six specimen depicted Devonian carbonates. Furthermore not every test essential for reservoir potential evaluations was conducted on those samples, as permeability measurements are missing. Table 1 shows the mean, minimum and maximum values of the most important petrophysical parameters of the Devonian carbonates.

Table 1: Petrophysical values of Devonian carbonates in the northeastern Rhenish Slate Mountains. Φ_{eff} = effective porosity, λ_{sat} = saturated thermal conductivity, v_p = P-wave velocity (Jorand et al. 2015).

	Φ_{eff} (%)	λ_{sat} ($Wm^{-1}K^{-1}$)	v_p (ms^{-1})
Mean	1.3	2.90	5,597
Min	0.4	2.76	4,999
Max	2.8	3.13	6,078

The petrophysical values of the present study will be compared to the ones of table 1 and results of outcrop analogue studies conducted in the Malm-carbonates of southern Germany in the end, in order to validate the results and make a statement about the suitability of the features in respect of deep geothermal reservoir potential.

4. RESULTS

For a structured presentation, the results of the present study are subdivided into facies determination, fracture analysis and petrophysical examinations.

4.1 Facies Determination

The facies determination on a macroscopic and microscopic scale depicts the first part of the present study, in order to carry out the subsequent tests and analyses in a facies-related way. As mentioned in chapter 3.1, the classification system and nomenclature of former studies is used. In the three quarries analyzed not all existing Devonian carbonate facies types have been detected, at least so far. Members of the Schwelm-facies and the Dorp-facies could be determined, while in the latter case only back- and fore-reef sub-types could be recognized. This is not unusual, as the reef-cores only account for minor portions of the Dorp-facies (Krebs 1974). Figure 4 shows four exemplary thin sections representing different occurring facies types of all the quarries examined.

The staining of thin section a), sampled on the seventh level of the Wuppertal-quarry, hypothesizes that the section mainly consists of calcite, as everything in the stained part of the sample turned reddish. According to Dunham (1962) and Embry and Klovan (1971) the sample can be classified as a bindstone with a micritic matrix. The porosity is mostly secondary moldic to fenestral, but interparticle and microporosity is also recognizable (Choquette and Pray 1970). Regarding the fossil content, algae and cyanobacteria dominate the assemblage, while no other allochems are detectable in the matrix. Most of these fossils primarily consist of unstable aragonite, which is easily dissolved (Flügel 2004). This could be the explanation for the fenestral porosity forming along the biogenic structures. The few existing allochems are not well rounded and the thin section is matrix supported. Therefore a low energy depositional environment underneath the constant influence of wave action is expected leading to the classification as Schwelm-facies according to Krebs (1974). Figure 3 shows that the carbonates in Wuppertal (Elberfeld is a district of Wuppertal) can represent each of the three main facies types of Devonian carbonates. As the sample was picked on one of the lower levels of the quarry, the classification as Schwelm-facies, which always forms the lower parts of the carbonate sequences, makes sense (Krebs 1967, 1974). Since Machel and Hunter (1994) only distinguish facies types influenced by reefal buildups - so within the Dorp-facies basically – their classification system is not applicable in this case.

Thin section b) was produced from a sample taken on level 5 in the quarry Hagen-Hohenlimburg. According to the staining it seems like the section consists almost exclusively of calcite, while X-ray powder diffraction (XRD) measurements carried out on the sample revealed the mineralogy to be composed of 77 % calcite, 19 % dolomite and 4 % quartz. Therefore sample b) can be described as a dolomitic limestone according to Harris (2006). The dolomitization is expected to be epigenetic, so related to fractures, schistosity or bedding planes and caused by hydrothermal fluids after burial (Krebs 1974). According to Dunham (1962) and Embry and Klovan (1971) the thin section is denominated as a packstone. The matrix is mainly micritic, but sparry portions are available, as well. Taking the porosity classification system of Choquette and Pray (1970) into account, fracture porosity and microporosity are on hand, while the pore space portion in general is relatively low. Crinoids and bryozoans account for the major share of allochems followed by thick-shelled bivalves, gastropods, ostracods and brachiopods. Although the fossil content is very versatile, corals and stromatoporoids, which are the main reef-building organisms in the Devonian, are not detectable. The sorting of the abundant allochems, representing fragments and reefal debris mainly, is quite poor in contrast to the rounding. Therefore, plus the dominance of crinoids, bryozoans and thick-shelled bivalves, which are typical fore-reef organisms, thin section b) is classified as Dorp-facies: fore reef (Krebs 1974, Machel and Hunter 1994). A further subdivision according to Krebs (1974) results in a denomination as 'light-gray crinoid-brachiopod facies', whereas Machel and Hunter (1994) call this type IIf.

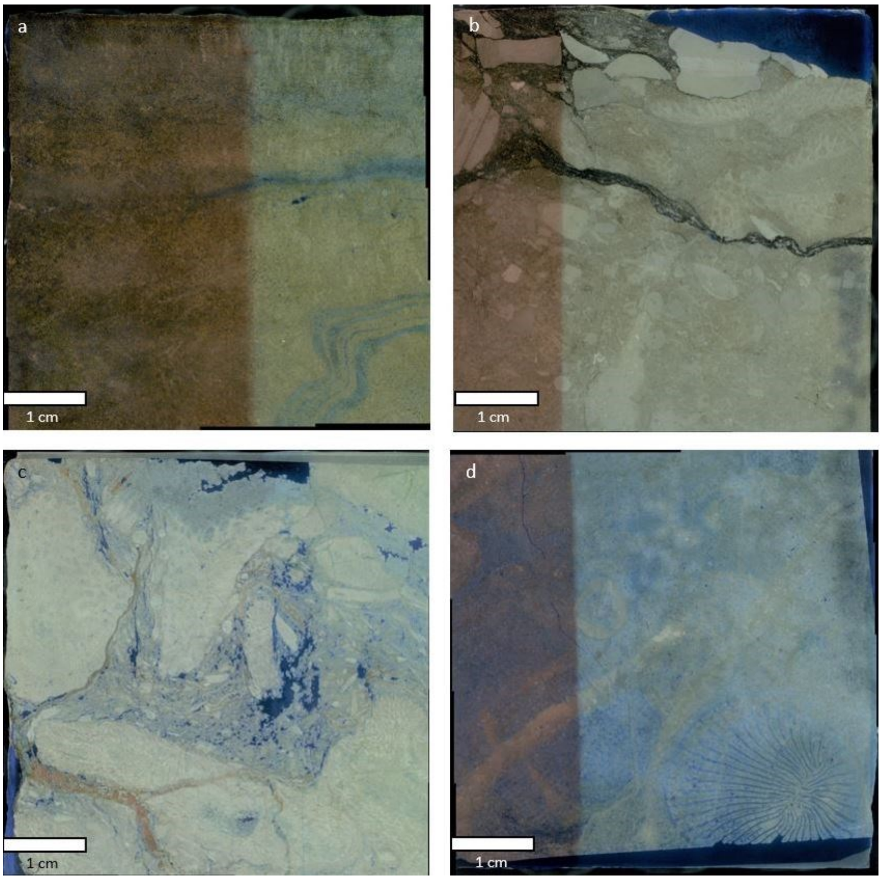

Figure 4: Thin sections of Devonian carbonates from quarries on the northern flank of the Remscheid-Altena Anticline. a) Schwelm-facies in Wuppertal, b) Dorp-facies: fore-reef in Hagen-Hohenlimburg, c) dolomitized Dorp-facies: fore-reef in Hagen-Hohenlimburg, d) Dorp-facies: back-reef in Hönne-Valley.

Thin section c) in the lower left part of Figure 4 was also sampled in Hagen-Hohenlimburg, this time on level 3. Here we see a major difference compared to the other specimen, as almost all minerals, even within the stained area, appear whitish. Only one calcitic vein colored in red is recognizable. This means the sample mainly consists of dolomite, which is evidenced by the XRD-results: 70 % dolomite, 30 % calcite, <1 % quartz. As mentioned in the description of thin section b), the dolomite formed epigenetically (Krebs 1974). According to Dunham (1962) and Embry and Klovan (1971) thin section c) represents a rudstone, although the classification is hindered due to the recrystallization process. The matrix is dolomitic. As you can see in Figure 4, the overall pore space volume is relatively high and the porosity types are vuggy and interparticle porosity mainly, while fenestral, interparticle and microporosity also occur (Choquette and Pray 1970). Large allochems are available in thin section c), which mainly depict bryozoans. Further fossils are hardly recognizable due to the dolomitization, but likely represent brachiopods, crinoids and stromatoporoids. The secondary alteration also complicates the facies classification according to Krebs (1967) and Machel and Hunter (1994). Because of the clearly discernible fossil content, which is made up of bryozoans, and the size of the fossil fragments, the depositional environment is expected to be proximal fore-reef, which was dolomitized after deposition.

Figure 4 d) shows a thin section sampled in the Lhoist quarry in the Hönne-Valley on level 6. All minerals in the stained part turned red, meaning that we can expect major calcite portions from a mineralogical standpoint. The designation as a rudstone to floatstone with a micritic matrix containing sparry fractions is applied according to Dunham (1962) and Embry and Klovan (1971). Using the porosity classification of Choquette and Pray (1970) secondary moldic porosity is prevailing, but intraparticle, fracture and microporosity are also existent. The fossil content is mainly composed of rugose corals and ostracods. Thin-shelled bivalves, gastropods, benthic foraminifers (Parathurammina) and small crinoid fragments are on hand, as well. Furthermore calcispheres are detectable hypothesizing - together with the fossil content, the matrix composition and the pore types - that the deposition took place in a back-reef environment within the Dorp-facies (Krebs 1974). According to Machel and Hunter (1994) the sample can be classified as facies IIIb.

4.2 Scanline Survey

As mentioned in chapter 2.2 up to 16 parameters were recorded for every fracture intersecting the particular scanlines. All together 760 fractures have been surveyed in the three studied quarries resulting in substantial data sets and a variety of plotting possibilities. For the evaluation of the reservoir potential the facies-related fracture spacing values, the mean trace length and the fracture type are of major importance due to their effects on the hydraulic conductivity of the formation (Lucia 2007, Markovaara-Koivisto and Laine 2012). As the differentiation of the different primary depositional facies types in the quarries is imprecise compared to microscopic facies analyses in the laboratory, the focus has been distinguishing between dolomitized and non-dolomitized sections for the scanline surveys.

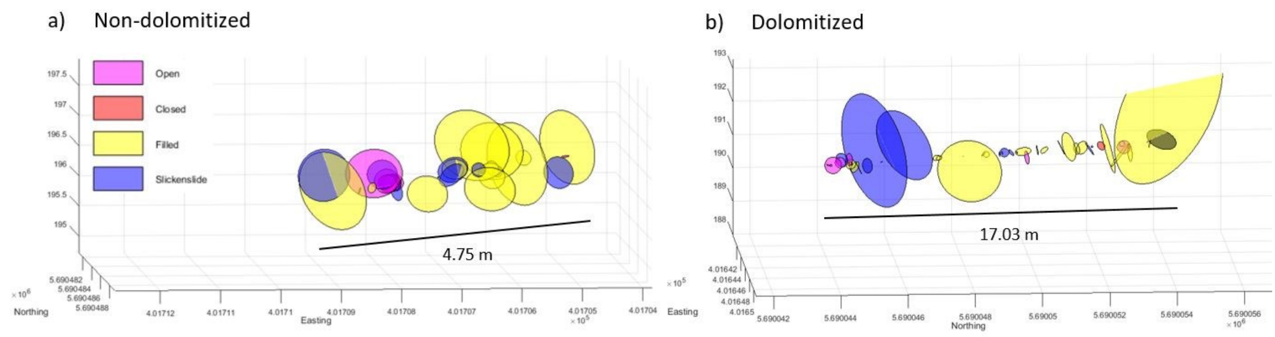

Figure 5: Comparison of a) non-dolomitized and b) dolomitized scanline sections from outcrops in the quarry Hagen-Hohenlimburg on level 3. Every fracture is represented by a coloured disc, while the coloration defines the fracture type (modified after Markovaara-Koivisto and Laine 2012).

Figure 5 exemplarily shows the comparison of two scanlines - one recorded in a dolomitized and the other in a mostly calcitic section. These scanlines were chosen because of the spatial proximity, as both were registered on the same level in Hagen-Hohenlimburg, and due to the fact that the major differences fall into place. Every fracture is represented by a colorized disc. The size of the disc represents the fracture length, the position shows the in-situ orientation and the color-coding is explained in the legend of Figure 5. As one can see in Figure 5 b), most fractures in dolomitic sections exhibit a decreased trace length compared to the ones in non-dolomitized parts. Furthermore the fracture density, which is the amount of fractures per meter, is typically higher in the calcitic scanlines. Regarding the fracture types the differences are not that pronounced, at least matching the portions of opened fractures, which bear the most important meaning regarding the reservoir potential. Table 2 displays the differences of these parameters taking all measured scanlines of the different quarries into account.

Table 2: Average values of different fracture properties for all scanlines recorded in the three examined quarries classified into non-dolomitized and dolomitized sections.

	length (m)	fracture density (m^{-1})	opened fractures (%)
Non-dolomitized	1.22	6.90	27.12
Dolomitized	0.47	5.62	25.22

4.3 Petrophysical Properties

On the laboratory scale the fracture properties of a certain formation or facies type are hard to consider. In this case the petrophysical matrix features, like the thermal conductivity, the effective and total porosity and the permeability, are measured. The interpretation of the petrophysical results focuses on the spatial differences and on distinguishing between dolomite and limestone, again, for two reasons. Firstly the facies determination is a work in progress, meaning that not every sample tested petrophysically is assigned to a certain facies type, especially not within the non-dolomitized units. The differentiation between dolomitized and calcitic samples, in turn, is more obvious and evidenced by XRD-measurements. Therefore this aspect can be taken into account. Furthermore, the petrophysical variations are more distinctive between dolomitized and non-dolomitized samples compared to the disparity of fore- and back-reef types, for instance. In the following sections every sample exhibiting a dolomite portion of more than 50 % is designated as dolomite.

Figure 6 displays the dry (λ_{dry}) and saturated (λ_{sat}) thermal conductivity, permeability (k) and P-wave velocity (v_p) plotted against the effective porosity (Φ_{eff}) of the Devonian carbonates in the study area. The particular quarries are illustrated in different colors, while the shape of the symbols reveals the dolomite content and the filling of the symbols stands for saturated or dry samples. Since several cores were drilled from single blocks sampled in the different quarries and lithologies, similar effective porosity values are measured resulting in the symbols being in-line relatively to the x-axis.

Figure 6 a), as expected, shows a decreasing trend of P-wave velocities with rising effective porosity values. A clear-cut spatial trend is not recognizable. The low average v_p-values and inverse trend with increasing Φ_{eff} of the dolomitic samples stands out. The former phenomena is caused by the elevated porosities in the dolomitic carbonates, while the latter is related to the chaotic pore space and fracture distribution detectable in most of the dolomite samples. Depending on the orientation of the discontinuities and partly large, drusy pore space portions, both of which are very numerous in the dolomitic samples, P-wave velocities can vary strongly and for instance rise with increasing effective porosities, if the main fracture orientation is in accordance with the measuring direction (Azhari and El Hassani 2013).

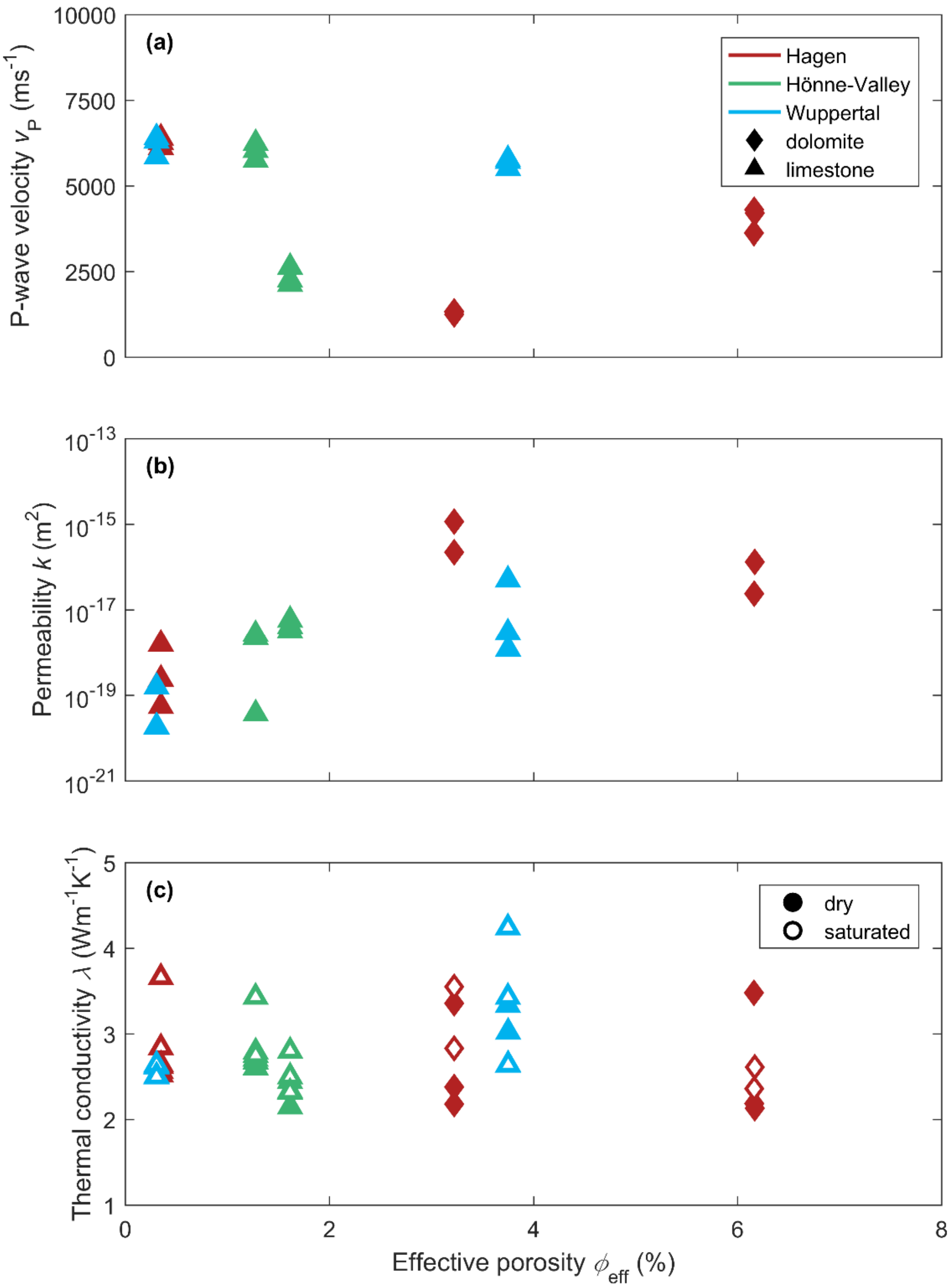

Figure 6: Petrophysical values of dolomitic and non-dolomitic samples of Devonian carbonates in North Rhine-Westphalia from the three examined quarries along the northern margin of the Remscheid-Altena Anticline. a) v_p vs. Φ_{eff}, b) k vs. Φ_{eff}, c) λ_{dry} and λ_{sat} vs. Φ_{eff}.

Figure 6 b) displays the k – Φ_{eff} plot. As the effective porosity represents the connected pore space, directly influencing hydraulic routing, a distinct upward trend of permeabilities with increasing Φ_{eff} is obvious. A spatial trend is not on hand. The dolomitic samples exhibit elevated values for both k and Φ_{eff} compared to the calcitic ones. Within this sample category, a slight decrease in permeability with an increasing effective porosity is recognizable contradicting the general trend, again. The reason could be the occurrence of large, drusy pore space within the dolomites for instance. In case it is located at the end face of the sample core, the effective porosity is elevated without necessarily accounting for the permeability. In general, however, this trend is not too pronounced.

Figure 6 c) contains information about dry and water-saturated thermal conductivities plotted against Φ_{eff}. Since water exhibits a higher thermal conductivity than air, saturated thermal conductivity values are supposed to be increased compared to the ones measured on dry samples (Engineering ToolBox 2003). This relation is detectable in Figure 6 c), as well. The only exception seems to be on hand for the dolomitic samples holding Φ_{eff}-values of around 6.2 %, but only two saturated cores have been measured in this case so the upper dry value is not accompanied by a saturated one, which would presumably be higher, as well. In general a slightly decreasing trend of thermal conductivities with an increase in Φ_{eff} is perceived, which could be expected due to the lower thermal conductivity of air or water compared to the minerals (Engineering ToolBox 2003). Analyzing the spatial variation by comparing the results of the different quarries, no obvious pattern is recognizable.

Making statements about the influence of the sampling locations is difficult, mainly because the calcitic samples of Wuppertal, exhibiting effective porosities of approximately 3.7 %, are out of place. Petrophysically these values rather are in accordance with the dolomitic samples of Hagen. The primary macroscopic evaluation classified these samples as dolomitic, as well, but the XRD-measurements revealed the dolomite content of only 8 %, while 92 % are calcite and < 1 % quartz. Excluding these samples, a spatial trend for the hydraulic parameters within the limestones becomes clear. An increase in k and Φ_{eff} from west to east, so from Wuppertal to Hönne-Valley, is now detectable.

5. DISCUSSION

The findings of the study shall be examined with regard to the geothermal reservoir potential of the Devonian carbonates in general and their particular facies types. Therefore the facies determination, which is still a work in progress, depicted the first part of the project work. Taking all examined samples into account, two of the main facies types for Devonian carbonates in central Europe according to Krebs (1974) have been detected so far. These are the Schwelm- and the Dorp-facies. The latter is subdivided into the fore-reef, reef-core and back-reef sub-facies, but reef-core samples have not been spotted. Hagen-Hohenlimburg is the only quarry of the three examined in the course of the present study, where dolomite was detected so far, but further XRD-analyses are required for a proper evaluation. According to Krebs (1974) the dolomitization occurred epigenetically meaning that no relation to a certain facies type is on hand. Special tests revealing the formation temperature of the dolomites and therefore its origin will be conducted in the course of the present study. As the facies analysis is not finished for all samples and due to the fact that the differences regarding the fracture and petrophysical properties are more pronounced comparing dolomitic and calcitic samples anyway, the subsequent scanline analyses and laboratory tests focused on distinguishing these types.

The scanline survey has been carried out to make statements about the fracture properties of the Devonian carbonates, which play an important role for the hydraulic connectivity and therefore the reservoir potential of a formation (Lucia 2007, Markovaara-Koivisto and Laine 2012). Taking all recorded scanlines into account and analyzing the most important features like trace length, fracture density and portion of opened fractures (table 2), it became clear that the calcitic sections exhibit favorable properties from a reservoir potential standpoint due to elevated values in all mentioned categories. Especially the increased mean trace length of the limy sections stands out. As the dolomitic sections were frequently covered with debris, clay etc., which was not the case for the limestone parts, trailing a single fracture along the outcrop wall within the dolomites has been hard at times, though. This matter of fact, however, is not expected to make up for the whole variation in trace length.

For being able to evaluate the petrophysical results of the present study, the findings are compared to the ones from existing researches like the one of Jorand et al. (2015).

Table 3: Comparison of mean petrophysical values from existing literature and results gained in the present study (Jorand et al. 2015).

	Φ_{eff} (%)	λ_{sat} ($Wm^{-1}K^{-1}$)	v_p (ms^{-1})
Jorand et al. (2015)	1.3	2.90	5,597
All samples	2.4	2.89	4,544
Non-dolomitic samples	1.5	2.91	5,293

Although partly different measurement methods have been used, table 3 shows that the different values are in agreement with each other, especially if the dolomitic samples are excluded. Since only six Devonian carbonate samples have been examined in the course of the study of Jorand et al. (2015) and dolomitic sections are quite rare, which is known from the field work, the XRD-measurements and the facies analysis, not taking the dolomites into account for this comparison seems justified. The relation generally validates the results of the present study.

For being able to make statements about the overall reservoir potential of the Devonian carbonates, the petrophysical values of the present studies are then compared to the ones gained in outcrop analogue studies in the Malm-carbonates of southern Germany, since several geothermal plants in the Munich area use the latter formation as deep geothermal reservoirs. As one can see in table 4, the petrophysical values of the Malm-carbonates are sub-divided into two main facies types, too, which are basin and massive facies. This is not directly matchable with the distinction between limestone and dolomite, but like the dolomites in the Rhine-Ruhr region, the massive facies possesses elevated thermal and hydraulic values. Furthermore the valuations and proportions are in accordance with each other. While the hydraulic results of the limestones in the Rhine-Ruhr area are decreased compared to the ones of the basin facies of the Malm-carbonates, the thermal conductivity of the former units is higher. The permeability of the dolomites in North Rhine-Westphalia is higher than the one of the massive facies in Bavaria, while the effective porosity is reduced and the thermal conductivity shows no difference. The comparison of the Malm- and Devonian carbonates hypothesizes that deep geothermal applications could be possible.

Regarding the petrophysical results, one limestone sample from Wuppertal falls out of place. The values are rather in accordance with dolomitic data and macroscopically this block was designated as dolomite, as well. The XRD-measurements, however, state that powder produced from this block consists of 92 % calcite. So there are two possibilities: either the calcitic units have a wider range of petrophysical values which should be proofed by carrying out more laboratory experiments or the XRD-results are not representative for the sample cores used for the tests. The second aspect could be traced back to mineralogical variations within a single block, for instance, and the fact that the powder for the XRD-measurements is not produced from parts of the sample core itself, but from the larger block. Therefore future examinations should use powder for XRD-measurements taken from the sample cores themselves or areas as close as possible to reduce the effect of possible small-scale mineralogical variations. In general more XRD- and petrophysical measurements are required to enhance the understanding of the facies-related and spatial variations.

Table 4: Comparison of petrophysical properties of the Malm-carbonates in southern Germany and the Devonian carbonates in the Rhine-Ruhr region (Homuth 2014).

Region / parameter	Munich (Homuth 2014)		Rhine-Ruhr	
Facies	Basin facies	Massive facies	Limestone	Dolomite
Thermal conductivity, dry ($Wm^{-1}K^{-1}$)	1.9	2.6	2.6	2.6
Effective porosity (%)	3.5	6.0	1.5	4.7
Permeability (m^2)	$5.0*10^{-17}$	$1.0*10^{-16}$	$5.0*10^{-18}$	$3.8*10^{-16}$

The burial history of the examined outcrop sections, which would provide valuable information about diagenetic alteration processes and their timing and, thus, the reservoir potential in general, is still unclear and will be examined in the following steps of the project work.

6. CONCLUSION

The present study investigates the deep geothermal reservoir potential of Devonian carbonates in the Rhine-Ruhr area. The superordinate goal of the region is to supply the existing district heating network with sustainable thermal energy like in the prototype area of Munich, where Upper Jurassic Malm-carbonates are used as reservoir formations. By comparing thermal and hydraulic results gained in the present study with values obtained in outcrop analogue studies examining the Malm-carbonates, a first statement about the reservoir potential of the Devonian carbonates can be made. The petrophysical values of the carbonate units of the Rhine-Ruhr region range within similar valuations and exhibit related proportions as the carbonates of the Munich area. Thus, a general suitability for reservoir purposes is assumed.

Another main question which should be answered in the course of the present study is the one, if there are certain facies-types being more promising to serve as a deep geothermal reservoir formation than others. Therefore facies analyses have been conducted. As the detailed facies determination, especially within the sub-types of the limestone units, is a work in progress and since the variations between calcitic and dolomitic samples is more pronounced for the fracture analysis and the petrophysical examination, these categories have been distinguished. The fracture properties hypothesize that the calcitic units are the ones to target, while the hydraulic properties of the dolomites are more promising. Therefore a clear-cut statement cannot be made so far.

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