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Numerical petrographic pore system analysis: Implications for geothermal reservoir characterization of the Muschelkalk in Northern Germany

S. Maerz[1], G. Winterleitner[1], N. Meier[1], D. Bruhn[1,2]

[1] Fraunhofer Institution for Energy Infrastructures and Geotechnologies; [2] Delft University of Technology

Summary

In this study, the effect of different Lower Muschelkalk Schaumkalk fabrics on pore system properties have been investigated to understand the permeability heterogeneity of this potential geothermal reservoir facies. A combination of permeability mapping and numerical petrographic pore system analysis has been used to identify high-permeability fabrics which are then analysed for their effective pore types. Locally concentrated zones of vug-formation as well as the occurrence of laminae dominated by molds of bivalves highly elevate permeability as compared to the typical “Schaumkalk” fabric with an inverted pore system dominated by moldic pores. The highest permeability measured is tied to the coquina fabric. The method presented offers a novel tool of numerical pore system analysis for determination of pore type properties and prediction of permeability heterogeneity at an unprecedented level of accuracy.

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Introduction

Carbonates are commonly marked by a weak correlation between porosity and permeability when measured with routine petrophysical methods (e.g., Mazzullo, 2004; Dernaika & Sinclair, 2017). They further exhibit a wide range of permeabilities for a given porosity value (Ehrenberg & Nadeau, 2005). This is mainly caused by subtle to profound variations in the primary depositional fabric, even within identical facies types, as well as multiple phases of differential diagenetic modification. This leads to a co-occurrence of ineffective and effective pore types, with the latter determining the magnitude of permeability at different spatial scales. Therefore, systematic analytical methods are required to improve the understanding of the mutual relationship between porosity and permeability which can be applied on multi-scale pore systems data. Zones of enhanced permeability in carbonate reservoirs can be subdivided into matrix, structural and diagenetic flow zones (Cross & Burchette, 2024). The scale of observation varies depending on the predominant flow zone type, requiring petrophysical methods to be adapted to meet the specific needs of a comprehensive petrophysical analysis. The hereby presented method of numerical petrographic pore system analysis is scale-independent and can be applied on every type of flow zone, ranging from microporosity scale (< 1 µm) up to fracture networks, cavernous porosity and bioturbated textures at core scale. In this study, we utilize pore geometry derived from digital image analysis as a proxy-parameter to quantify pore type effectiveness and explore permeability heterogeneity of the matrix-porosity-dominated Middle Triassic Muschelkalk carbonates in the subsurface of the Northern Germanic Basin.

In recent years, the Middle Triassic Muschelkalk has been in the focus of reservoir characterization studies for geothermal applications and gas storage in the Northern Germanic Basin (e.g., Noack & Schröder, 2003; Käsbohrer & Franz, 2024). In particular, the Lower Muschelkalk (Anisian) Schaumkalk ("foamy limestone") facies exhibits locally intermediate to high petrophysical properties, with permeabilities exceeding 10,000 mD as measured in one core close to the city of Berlin, Germany (Noack & Schröder, 2003). This potential reservoir facies has been deposited within shallow-water ooid shoal systems as part of the inner ramp depositional setting of the epeiric Lower Muschelkalk ramp. In Southern Germany, the entire Middle Triassic Muschelkalk is outcropping in numerous quarries and cliffs due to the early Tertiary uplift of the entire Mesozoic strata caused by the formation of the Upper Rhine Valley. This excellent outcrop conditions allowed for a detailed reconstruction of the distribution, geometry, and facies variation within a sequence stratigraphic framework of the Muschelkalk ooid shoal systems (e.g., Palermo et al., 2010; Petrovic & Aigner, 2017; Warnecke & Aigner, 2019). In Northern Germany instead, similar detailed assessments of the facies architecture and reservoir compartmentalization are rare to absent due to the scarcity of subsurface and analogous outcrop data from the Northern Germanic Basin. Consequently, these local variations of shoal thicknesses, lateral extension, sedimentary fabrics, and petrophysical properties, complicate the evaluation of the Schaumkalk reservoir potential. For this study, we have investigated different outcrops of variable Schaumkalk fabrics with the goal of quantitatively analysing effective porosity and permeability heterogeneity within these ooid shoal deposits.

Methodology

The studied outcrops are located along cliffs and quarries along the rivers Unstrut and Saale in Saxony-Anhalt, Germany. They represent outcrops that are in closest proximity to their subsurface equivalents in Northern Germany. There, the Lower Muschelkalk carbonates occur as generally continuous beds of Schaumkalk facies intercalated with finer-grained micritic beds**.** Bed thicknesses vary between decimetre to metre thick beds, with localized accumulations of thick oolitic deposits which are partially pinching out. Although ooid shoal deposits are often considered to exhibit homogenous sedimentary fabrics, their internal structures show a variable abundance of non-skeletal versus skeletal grains, variations in micrite content, and differential diagenetic modification. This high variation in ooid shoal fabrics can also be observed in modern day analogous ooid shoal settings. Rock slabs with edge lengths greater than 10 x 10 cm have been collected from the outcrops and polished for all subsequent analysis. The different Schaumkalk fabrics analysed for this study include: (F1) Grainstones dominated by non-skeletal grains with abundant oomoldic porosity; (F2) Pack- to grainstones dominated by skeletal grains with abundant moldic porosity; (F3) Grainstones with non-skeletal and skeletal grains with vuggy and intercrystalline porosity; (F4) Grainstones dominated by non-skeletal grains with oomoldic pores and frequent laminae of bivalve molds; (F5) Grain- to rudstone dominated by bivalve molds, representing a typical coquina texture. The initial step of the numerical petrographic workflow presented includes the creation of permeability maps derived from probe-permeameter measurements applied on the polished rock slabs (Figure 1). This allows for detecting zones of different magnitudes of permeability, categorized into low (< 100 mD), intermediate (100 - 500 mD), and high permeability (< 500 mD). Each sample slab was subdivided into a grid with cell sizes of 1 x 1 cm, ensuring a systematic determination of permeability through probe-permeametry. Due to the penetration depth of 3 cm of the injected nitrogen, it is required to use rock slabs with a thickness greater than the penetration depth to ensure no leaking of gas and thus, incorrect permeability values.

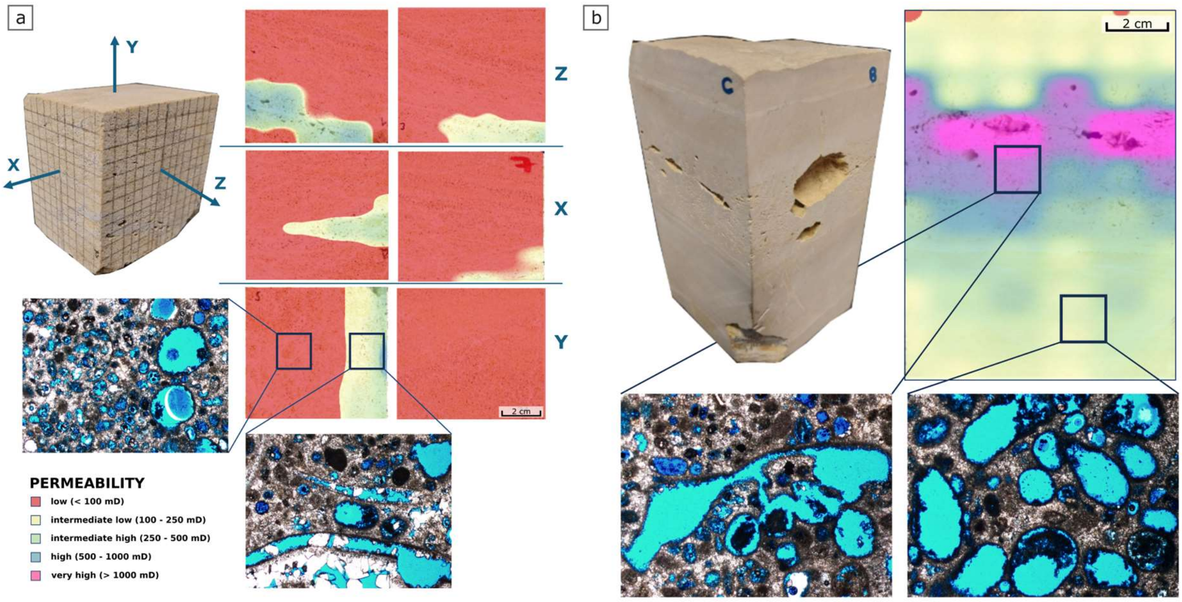

Figure 1 *Permeability Maps. (a) Permeability maps of Schaumkalk fabric F4 indicates enhanced permeability along laminae dominated by bivalve molds, measured in three different orthogonal orientations. Molds of bivalves increase permeability due to their big size and elongated shape in contrast to the rather weakly interconnected pore system dominated by oomoldic pores, solely. (b) Permeability map of Schaumkalk fabric F3 shows increasing permeability towards an interval of vug abundance. This is caused by interconnection of previous isolated oomoldic pores by dissolution.*

In a next step, blue-dyed thin sections were prepared from each permeability zone identified, and analysed with digital image analyse. For this study, the software JMicroVision (Roduit, 2006) has been used to segment the sedimentary fabric into its pore and its solid phase. Then, image analysis porosity is calculated, and pore space geometry is captured. By using a semi-automated classification based on pore geometry, the pore space is subdivided into different pore type classes, based on the classification scheme of carbonate pore types by Choquette & Pray (1970). Pore-type-specific size and shape complexities are then utilized to numerically characterize pore type properties, where pore size represents the pore volume (i.e., porosity) and pore shape complexity reflects pore interconnectivity (i.e., permeability). By calibrating the previously measured permeability values with the pore-type-specific shape complexity, the contribution of each pore type to total permeability is finally calculated (Maerz, 2020). This leads to a quantitative assessment of how effectively each pore type contributes to fluid flow pathways through pore throats, thereby influencing the varying magnitudes of permeability associated with each type of pore.

Results

Based on the evaluation of pore type effectiveness calibrated with measured permeability, three Schaumkalk fabrics with enhanced permeabilities have been identified: Fabrics with laminae of bivalve molds (i.e., F4) show enhanced permeability values up to 500 mD in proximity to the laminae as compared to the rather low-permeability (< 50 mD) textural areas which are located in distance from the laminae. This is caused by the high interconnectivity of the bivalve molds within the laminae (Figure 2). Fabrics including intervals of centimetre-sized vuggy pores (i.e., F3) show permeability values exceeding 1,000 mD in proximity to the vugs, locally reaching up to 3,000 mD (see Figure 1). This is caused by the extremely high interconnectivity of the touching vugs (sensu Lucia, 1995) in this specific texture as determined by pore geometry (Figure 2). However, permeability rapidly decreases to less than 50 mD within a few centimetres distant from the vugs. Thus, high-permeability zones in this specific fabric are restricted to a few centimetres of vuggy porosity intervals. Finally, the Schaumkalk samples analysed which display a coquina texture (i.e., F5) exhibit the highest pore interconnectivity throughout the entire fabric of the rock slab, resulting in permeability values reaching up to 4,000 mD. Therefore, this Schaumkalk fabric encompasses the most effective and therefore most permeable pore system structure. Schaumkalk fabrics which display a rather typical oolitic texture with partially dissolved non-skeletal and/or skeletal grains (i.e., F1, F2) show low permeabilities despite moderate to high porosity values of 18 % in average. This can be attributed to the absence of pore throats and the resulting low interconnectivity of moldic pores in these Schaumkalk fabrics, as determined by numerical petrographic analysis (see Figure 2).

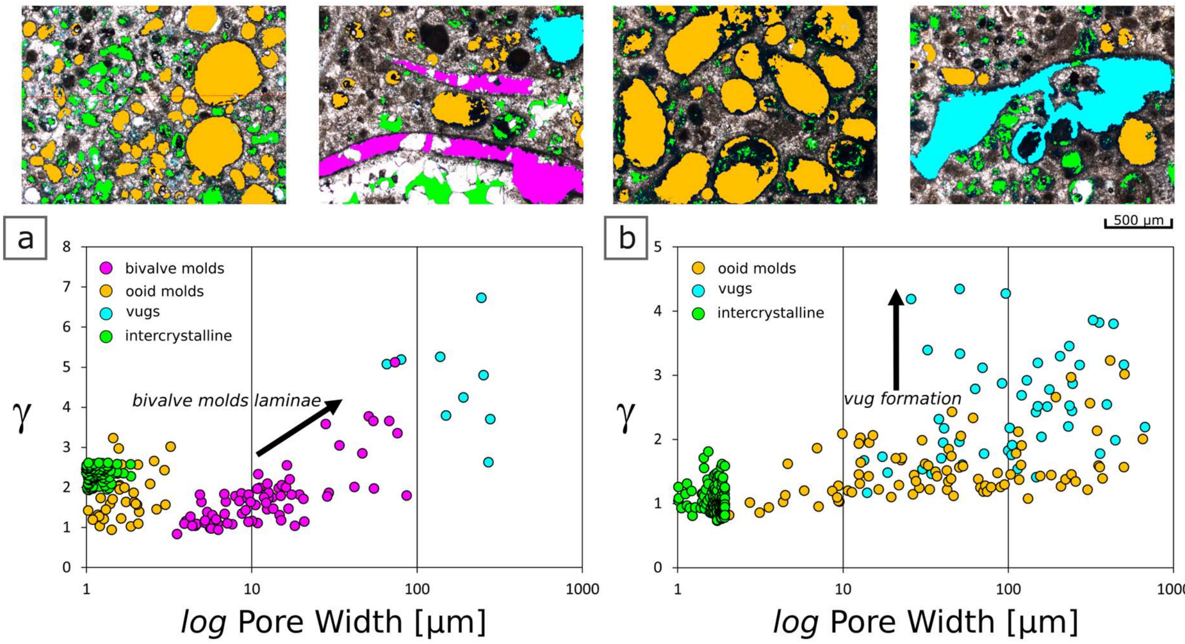

Figure 2 *Numerical Petrographic Analysis. (a) Pore width versus pore shape complexity γ (sensu Anselmetti et al., 1998) of Schaumkalk fabric F4 shows enhanced pore size and shape complexity in fabrics with abundant effective bivalve molds and few vugs. (b) Pore size and shape complexity in Schaumkalk fabric F3 is highly enhanced by the introduction of effective vugs.*

Conclusions

In this study, the effect of different Lower Muschelkalk Schaumkalk fabrics on pore system properties have been investigated to understand the permeability heterogeneity of this potential geothermal reservoir facies. A combination of permeability mapping and numerical petrographic pore system analysis has been used to identify high-permeability fabrics which are then analysed for their effective pore types. Locally concentrated zones of vug-formation as well as the occurrence of laminae dominated by molds of bivalves highly elevate permeability as compared to the typical Schaumkalk fabric with an inverted pore system dominated by moldic pores. The highest permeability measured is tied to the coquina fabric. The method presented offers a novel tool of numerical pore system analysis for determination of pore type properties and prediction of permeability heterogeneity at an unprecedented level of accuracy.

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