University of Miskolc

Mikoviny Sámuel Doctoral School of Earth Sciences

Head of the doctoral school
PROF. DR. PÉTER SZŰCS
Full professor, vice rector

APPLICABILITY OF CT (COMPUTED TOMOGRAPHY) FOR PORE NETWORK EXTRACTION AND CHARACTERIZATION

New scientific achievements of Ph.D. thesis

Written by HASAN ATRASH

Scientific advisor: DR. FELICITÁSZ VELLEDITS

Professor associate

2023. Miskolc, Hungary

1. Scientific Background and Objective of the Dissertation

Carbonate reservoir rocks have a complicated pore system as a result of sedimentological and diagenetic processes (Scoffin 1987; Arns et al. 2004).

Contrary to siliciclastic reservoirs, where the main component is the chemically resistant quartz, carbonate minerals (calcite and aragonite) are very susceptible to extensive diagenetic change, dissolution, cementation, recrystallization and replacement at ambient conditions in a variety of diagenetic environments or during a succession of diagenetic episodes.

In recent years, the use of micro X-ray computer tomography (micro-XCT) imaging to assess the pore space of reservoir rocks has grown in popularity. This technique depicts 3D pore network at micron scale (Brunke et al. 2010), which can provide valuable information on the complex pore system of rock samples and their interrelationships between porosity and permeability.

Accurate characterization of pore structures in carbonate rocks is critical for understanding their petrophysical properties, which directly impact reservoir performance. To achieve a comprehensive understanding, pore network models need to capture the complex geometry and topology of the pore space. In recent years, high-resolution X-ray computed tomography (CT) has emerged as a valuable tool for geological investigations due to its non-destructive nature and ability to generate detailed images resembling serial sections of the rock sample.

Interpreting and analyzing X-ray tomographic images require effective image segmentation techniques. Image segmentation plays a vital role in representing the real pore space in terms of its geometric and topological characteristics, enabling accurate pore network modeling. While various image segmentation techniques have been proposed in the literature, there is no universally applicable algorithm that consistently produces accurate results for all types of data. This poses a challenge in accurately characterizing pore structures in carbonate rocks using X-ray CT data.

The objective of my Ph.D. thesis is to conduct a comprehensive research study focusing on three key components. By addressing these components, the research aims to advance our understanding of carbonate reservoirs and contribute to improved reservoir characterization and evaluation practices.

The first component of the research involves developing and refining image segmentation techniques specifically tailored for carbonate rocks. This will involve exploring advanced algorithms and methodologies to accurately delineate and extract pore structures from X-ray CT images. By overcoming the challenges associated with image segmentation, the research aims to provide reliable and precise representations of the pore space.

The second component entails a comparative analysis between productive and dry intervals within the studied reservoir. This analysis will involve characterizing and quantifying the variations in pore characteristics, such as pore size distribution, pore connectivity, and pore throat sizes, between the two intervals. Understanding these differences is crucial for identifying key factors influencing reservoir productivity and can aid in optimizing reservoir management strategies.

The final component focuses on the petrophysical characterization of the reservoir rocks. This involves analyzing various petrophysical properties, including porosity, permeability, and fluid saturation, to gain insights into the reservoir's fluid flow behaviour and potential productivity. Integrating the findings from image segmentation and the comparative analysis of productive and dry intervals, the petrophysical characterization will contribute to a more accurate assessment of reservoir quality and potential hydrocarbon recovery.

2. Applied Methods and Investigations

An extensive analysis was undertaken to explore the intricate characteristics of the Sarmatian limestone. The primary focus was on understanding the structure of the pores and identifying the similarities and differences in the pore space within these samples, given that these rocks have undergone multiple cycles of diagenesis. Throughout their geological history, these limestone formations have experienced numerous dissolution events.

To fully comprehend the hydrocarbon reservoirs, it is crucial to investigate not only the 3D pore network, but also the sedimentological and diagenetic processes that have shaped them. Depicting the pore network in 3D on a micron scale may not provide a complete understanding of the geological processes involved in hydrocarbon exploration. Therefore in my study I employed a combination of micro-CT analyses, lab measurements and facies analyses. Using these methods, I can elucidate the reasons behind one section of the reservoir yielding productive results while the other remains dry.

To ensure representative samples, the selection process involved careful consideration of well logs and an in-depth examination of the existing literature on the Sarmatian limestone's geological history. Ultimately, four samples, two from the upper part and two from the lower part, were chosen for further investigation. These samples were obtained through plugs extracted from the main cores, and thin sections were prepared both horizontally and vertically to facilitate thorough analysis.

Laboratory measurements were conducted on the four plugs, including helium porosimetry and nitrogen permeability tests, providing valuable insights into the porosity characteristics and fluid flow properties. Additionally, smaller plugs were extracted from each of the main plugs to perform CT measurements. Each sample underwent a dedicated CT scan, resulting in a total of four scans. Sophisticated image processing techniques were then applied to analyse porosity and pore morphology in detail.

Given the challenges associated with image segmentation and the need to enhance accuracy, various machine learning techniques (ML) were explored. Unsupervised ML techniques such as k-means clustering and fuzzy c-means clustering were utilized, along with entropy techniques, including fuzzy entropy and minimum cross-entropy. To assess the accuracy of the segmentation, supervised ML techniques such as naïve Bayes and k-fold cross-validation were employed.

Upon successful segmentation of the pore space, 3D pore network models were generated, employing hybrid algorithm called the Distance Ordered Homotopic Thinning (DOHT) method by Pudney (1996, 1998). Enabling a comprehensive investigation of pore properties. This encompassed a thorough examination of pore size, pore connectivity, and channel length distribution. Comparisons were made among the depicted pores from each sample to gain valuable insights into the similarities and differences among them.

To gain further understanding of fluid behaviour within the studied samples, fluid flow experiment simulations were conducted on the generated pore networks. These simulations provided valuable data on fluid flow characteristics, facilitating a comprehensive evaluation of the reservoir's fluid dynamics.

My study aimed not only to depict the pore network of the productive and dry carbonates but also to contribute significantly to the characterization of the deposits. I prepared thin sections from the four samples using blue-stained resin and performed microfacies analyses to understand the sedimentological and diagenetic history that made one part of the rock sequence productive and the other dry.

Through the application of these rigorous methods and investigations, a comprehensive understanding of the pore structure and fluid behaviour in the Sarmatian limestone will be achieved, contributing significantly to the field of reservoir characterization and evaluation.

3. Scientific results

My research focused on characterizing the origin and types of pores in the Sarmatian limestone, considering the distinct geological environments of the upper and lower intervals in the studied area. My research has successfully described the origin and types of pores present. I have identified various pore types within these intervals and examined the effects of dissolution during diagenesis on their formation.

3.1 First thesis

My investigation has revealed that two diagenetic environments, meteoric phreatic and marine diagenesis, have played significant roles in the evolution of the pore system. During meteoric diagenesis, I observed the advancement and development of porosity in the carbonates. The first diagenetic environment is characterized by the presence of aggressive fluids in shallow waters that rapidly dissolve the sedimentary carbonate minerals, thereby creating secondary porosity.

In contrast, in the marine environment, cementation emerges as the predominant and most active diagenetic process, exerting a profound influence on porosity modification. Where most of the channels and the pore voids were filled with mosaic calcite and calcite mud. My findings indicate the occurrence of three types of cementations within the studied samples: dogtooth cement, blocky cement, and bladed cement. My findings highlight the complex interplay between dissolution and cementation during both meteoric and marine diagenesis. These diagenetic processes have a profound impact on the pore system within the Sarmatian limestone. By elucidating the specific origins, types, and effects of pore formation, my research contributes to a more comprehensive understanding of reservoir characterization. These insights are valuable for enhancing reservoir evaluation and management strategies.

3.2 Second thesis

I developed an image analysing method to analyse images and characterize the pore space by employing unsupervised machine learning where different ML techniques was tested including clustering and entropy techniques for classifying the pore grayscale values of the image pixels. Subsequently, the supervised machine learning method, Naïve Bayes, was employed to enhance the classification process. The Naïve Bayes is a probabilistic algorithm that calculates the likelihood of a data point belonging to a particular class based on the observed features. By considering the probability distribution of gray values, the model can estimate the likelihood of each pore being classified into different categories K-fold cross-validation is a technique that helps assess the generalization capability of the model. The accuracy of the model was the highest using type-2 fuzzy entropy. In addition, I assess the accuracy of the classification results through two approaches: visual inspection and a comparison of the pore size distribution generated by each method. Furthermore, I compare the results obtained from my methods with a ground truth image, which was created through manual annotation and labelling.

Overall, the Type 2 fuzzy entropy classifier performed the best, achieving the highest AUC value of 0.984 and the highest CA, F1-score, precision and recall values among all classifiers. The minimum cross entropy classifier also performed well, with an AUC value of 0.974 and a CA of 0.946. The k-means and fuzzy c-means classifiers achieved a slightly lower performance, with CA values of 0.877 and 0.888, respectively. Both classifiers also had a higher number of misclassified pixels than the other two classifiers, with fuzzy c-means having the highest number of misclassified pixels at 403,100. The reported gray intensity range of the misclassified pixels was similar for all classifiers, ranging from 85 to 112. However, the Naive Bayes showed relatively reasonable pore size distribution, and the resulting binarized image was more realistic in comparison to the original image and reference images. This comprehensive evaluation process allows to validate the effectiveness and reliability of my classification techniques in accurately characterizing the pore space.

3.3 Third thesis

By evaluating the 3D pore network parameters for the examined samples, I reached the following results:

- Sample 1966 (upper part) showed 24% porosity from image analysis and 25% from the He method in the lab. The average pore size was 0.0609, with some as large as 0.132. The average coordination number was 10, indicating high connectivity, reaching 35 in some cases. Pores and throats showed a correlation, especially for throat radii smaller than 65 microns. Larger throat radii were associated with higher coordination numbers.

Similarly, sample 1967 (upper part) had 27% porosity from image analysis and 25% from the He method. The average pore size was 0.0535, with some as large as 0.163. The average coordination number was 5, with a maximum of 45, indicating significant connectivity. Pores and throats showed a correlation, particularly for throat radii smaller than 65 microns. Larger throat radii were associated with higher coordination numbers, confirming the relationship between pore size, throat size, and connectivity.

3.4 Fourth thesis

Sample 1979 (lower part) exhibited an average porosity of 11.9% based on XCT images. A 3D analysis of the pore space revealed that isolated pores were the predominant form in the sample. No connections between the pores were observed, with only individual macro and micro pores present. The majority of the channels were filled with carbonate cement, as confirmed during the thin section investigation. However, a few random pore connections were detected. The pore radius ranged from 4 µm to 15 µm, with the most common pore size being 9 µm.

Similarly, sample 1980 (lower part) had an average porosity of 14% as determined from XCT images. The 3D analysis indicated that isolated pores were the dominant form in this sample as well. Similar to sample 1979, pore connections, existed only as solitary macro and micro pores. The majority of channels were filled with carbonate cement, which was further confirmed through thin section investigation. A few scattered pore connections were observed randomly. Microscopic analysis revealed similar characteristics in sample 1979. The matrix was dissolved and subsequently filled with mosaic calcite. The pore radius ranged from 4 µm to 40 µm, and the most prevalent pore size was 13 µm.

3.5 Fifth thesis

When comparing the 2D pore volume fraction to the calculated 2D fractal dimension, an interesting trend was observed in the upper part of both samples. A direct relationship between the porosity and the fractal dimension. Additionally, the 2D fractal dimension exhibited high values ranging between 1.65 and 1.67, indicating the presence of irregular pore shapes and rough pore surfaces. The pore structure displayed complex and irregular shapes for these samples from the upper part (1966 and 1967). However, for the lower interval samples (1979 and 1980), no correlation was found between the pore volume and the fractal dimension. The pores in these samples exhibited irregular and complicated shapes, regardless of their sizes. This irregularity persisted throughout all depth intervals studied for the fourth samples.

3.6 Sixth thesis

In order to study the reservoir properties and understand the fluid flow patterns, I have selected a region of interest within the sample for fluid flow simulation experiments. The sample was encapsulated on four faces, creating a controlled experimental setup. To guide the flow along a specific direction, experimental setups were added to two opposite faces of the sample. This setup allows to investigate the flow behaviour in three directions: X, Y, and Z. By repeating this process, I analysed and evaluated the flow patterns and characteristics in each direction.

The laboratory measurements recorded permeability values of 33.1 mD for sample 1966 and 54.32 mD for sample 1967. In contrast, the permeability derived from the images was higher, with values of 190 mD for sample 1966 and 880 mD for sample 1967. This difference in permeability can be attributed to the selection of a highly porous region of interest for numerical simulation, specifically focusing on understanding the fluid flow behaviour within the pore space. Furthermore, it is important to acknowledge the presence of inherent uncertainty in the permeability estimation due to various factors, including the limitations of the imaging technique and the methods employed for image processing. These factors can introduce potential errors and biases that may impact the accuracy of the derived permeability values. Therefore, while the derived permeability values from the images may provide valuable insights into the fluid flow behaviour within the pore space, it is essential to consider and account for the inherent uncertainties associated with the imaging process and subsequent analysis.

3.7 Seventh thesis

In Sample 1966, the flow behaviour was analysed in three directions: X, Y, and Z.

In the X direction, disconnected pores and low velocities were observed, indicating potential flow barriers and resistance. The Y direction showed higher velocities and favourable fluid pathways within the pore network. The Z direction had lower velocities and fewer streamlines, suggesting less momentum and lower flow rates compared to the other directions.

In Sample 1967, a similar analysis revealed a consistent and relatively high velocity in the X direction, with both favourable and constricted flow regions. The Y direction exhibited high velocities and favourable flow conditions, while the Z direction showed lower velocities and fewer streamlines, indicating reduced momentum and flow rates compared to the X and Y directions.

3.8 Eighth thesis

In Sample 1966 and 1967, the flow behaviour was analysed using the average Y and Z component velocities plotted against the X component. The plot showed changes in flow direction and velocity along the X axis. A prominent peak in the centre indicated a concentrated area of higher flow magnitude, while fluctuations between positive and negative directions were observed. Towards the end of the X axis, there were additional peaks suggesting specific flow patterns or structural elements influencing velocity changes. The average Z component velocity initially varied between positive and negative values but eventually stabilized with no significant variation.

3.9 Ninth thesis

In both Sample 1966 and Sample 1967, the analysis of flow rate with respect to throat radius reveals a consistent pattern. Initially, as the throat radius increases, the flow rate rises, reaching its peak at specific values - 12.5 to 18 microns in Sample 1966 and 10 to 20 microns in Sample 1967. Beyond these optimal ranges, the flow rate diminishes as the throat radius continues to expand. This behaviour is attributed to the interplay between pressure drop and fluid velocity, highlighting the critical role of throat radius in determining flow rate.

The influence of channel length on flow rate follows a similar trend in both samples. As channel length increases, the flow rate initially increases, peaking at specific values - 50 to 100 microns in Sample 1966 and 30 to 60 microns in Sample 1967. However, exceeding these optimal ranges results in a decline in flow rate. The initial increase is primarily driven by reduced flow resistance in longer channels, offering more space for fluid to flow through. The subsequent decline is due to factors like increased frictional losses and the development of laminar flow patterns, which limit the flow rate.

3.10 Tenth thesis

The effective formation factor was calculated through the effective formation factor calculation module in Avizo. The formation factor helps in evaluating the flow behaviour and assessing the overall fluid flow potential within the porous medium. The reservoir potential appears to be relatively homogeneous in the X and Y directions in both samples (1966 and 1967), suggesting a rather uniform distribution of the formation factors. This shows that the formation factor is generally consistent in these directions, resulting in less variety in the behaviour of fluid flow. On the other hand, an apparent feature in the reservoir potential can be seen while in the z direction. In the midst of the samples, there occurs a cutoff or a change in the formation factor. This cutoff denotes a change or break in the connectivity or pore structure in the Z direction.

3.11 Eleventh thesis

The 3D pore analysis of samples 1979 and 1980 revealed the presence of isolated pores distributed randomly throughout the samples, indicating a lack of connectivity. This characteristic renders the samples impermeable. Lab measurements confirmed the low permeability of these samples, with recorded values of 0.0721 mD for sample 1979 and 0.0037 mD for sample 1980. These low permeability values can be attributed to the presence of sub-micron pores that are below the resolution of the imaging technique, specifically at the 4-micron range, making them undetectable in the images.

4. Applicability of the results

The results obtained from the analysis of Sarmatian carbonates have several practical implications and applications. Firstly, the findings provide valuable information on the microstructural features and development history of the pores space and the history of the formation of the pores. Furthermore, the analysis of these carbonate samples has implications for the evaluation and prediction of reservoir properties. Through the examination of pore structures and connectivity can aid in predicting the fluid flow behaviour and reservoir quality of similar carbonate rocks. This information is crucial for the exploration and production of hydrocarbon resources in carbonate reservoirs.

Additionally, the results of the flow behaviour analysis provide insights into the fluid flow patterns within the pore network of the studied samples. Understanding the flow behaviour and connectivity of pores is essential for planning reservoir development and optimizing production strategies.

Furthermore, the observations of irregular pore shapes, rough pore surfaces, and the lack of pore connectivity in some samples contribute to our understanding of the heterogeneity and complexity of carbonate reservoir systems. This knowledge can help in refining reservoir models and improving reservoir characterization and simulation techniques.

5. List of publications that discuss the topic of the dissertation

5.1 Articles and proceedings

Hasan Al Atrash, Felicitász Velledits (2020) CT based analyses of pore network of reservoir rocks. Geosciences and Engineering, Vol. 8., No 13 pp. 167-184.

Hasan Al Atrash, Felicitász Velledits (2022) Phase segmentation optimization of micro x-ray computed tomography reservoir rock images using machine learning. Geosciences and Engineering, Vol. 10, No. 15 pp. 63 79. https://doi.org/10.33030/geosciences.2022.15.063Geosciences and Engineering.

Hasan Al Atrash, Felicitász Velledits (accepted in press) Comparing Petrophysical Properties and Pore Network Characteristics of Carbonate Reservoir Rocks Using Micro X-ray Tomography Imaging and Microfacies Analyses. GEM – International Journal on Geomathematics.

Hasan Al Atrash, Felicitász Velledits (2022) Image segmentation and optimization of X-ray computed tomography images of porous materials; quantitative 3D characterization of the pore space. Abstract. 22. International Congress on Geomathematics in Earth- and Environmental Sciences. Pécs, Hungary 2022.05.19. - 2022.05.21. 33025660. p 69.

Hasan Al Atrash, Felicitász Velledits (2023) Pore network characterization and permeability estimation: application of XCT in pore network analysis and flow analysis in porous medium. Abstract. Meeting of young geoscientists Nagybörzsöny Hungary, 2023.31.03 – 2023.01.04. Pp55-56

5.2 Presentations on international conferences

Hasan Al Atrash, Felicitász Velledits (2021) Image segmentation of X- ray computed tomography data of porous material: a review of global and locally adaptive algorithm. PhD Student Fórum University of Miskolc 2021 November 18.

Hasan Al Atrash, Felicitász Velledits (2022) Image segmentation and optimization of X-ray computed tomography images of porous materials; quantitative 3D characterization of the pore space. 22. International Congress on Geomathematics in Earth- and Environmental Sciences. Pécs, Hungary 2022.05.19. - 2022.05.21.

Hasan Al Atrash, Felicitász Velledits (2023) Pore network characterization and permeability estimation: application of XCT in pore network analysis. Meeting of young geoscientists Nagybörzsöny, Hungary, 2023.31.03 – 2023.01.04.

6. References

Scoffin T.P. (1987). An introduction to carbonate sediments and rocks. Blackie. Glasgow and London. 1-274.

Arns, C. H., Robins, V., Sheppard, A. P., Sok, R. M., Pinczewski, W. V., & Knackstedt, M. A. (2004). Effect of network topology on relative permeability. Transport in Porous Media, 55(1), 21-46. https://doi.org/10.1023/B:TIPM.0000007252.68488.43

Brunke, O., Santillan, J., Suppes, A. (2010). Precise 3D dimensional metrology using high resolution X-ray computed tomography (μCT). In Developments in X-Ray Tomography VII, vol. 7804, pp. 203-215. https://www.ndt.net/?id=9215

Pudney, C. (1996). Distance-based skeletonization of 3D images. Proceedings of Digital Processing Applications (TENCON'96), vol. 1, pp. 209–214.

Pudney, C. (1998). Distance-ordered homotopic thinning: a skeletonization algorithm for 3D digital images. Computer Vision and Image Understanding, 72(3), 404–413.