Proceedings Paper:

Hussein, D, Lawrence, J, Rashid, F et al. (2 more authors) (2018) Developing pore size distribution models in heterogeneous carbonates using especially nuclear magnetic resonance. In: Engineering in Chalk: Proceedings of the Chalk 2018 Conference. Engineering in Chalk, 17-18 Sep 2018, London. ICE Publishing , pp. 529-534. ISBN 978-0-7277-6407-2

https://doi.org/10.1680/eiccf.64072.529

Developing pore size distribution models in heterogeneous carbonates using especially Nuclear Magnetic Resonance

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ABSTRACT: Petrographical examination of thin sections, scanning electron microscope (SEM) analysis, helium porosimetry, gas permeametry, low field Nuclear Magnetic Resonance (NMR) spectrometry, and Mercury Injection Capillary Pressure (MICP) measurements of cored samples were investigated in order to understand pore size distribution models in the heterogeneous carbonate formations of the Euphrates and Jeribe formations, Kurdistan. These techniques provide petrophysical parameters, which include porosity, permeability, pore size distributions and pore-throat size distributions. Relaxation time distributions (T_2) of the NMR data were combined with pore size measurements derived from the thin section and SEM analysis to construct pore size distribution models in high and low reservoir quality carbonates with their different diagenetic histories.

Three pore size categories were identified, each with unique NMR behaviour and different pore types based on the petrophysical and petrographical data; these were: (1) pore diameters smaller than 1 µm which had a short relaxation time equal to or less than 200 ms; (2) pore diameter ranging from 1 µm to 4 µm which had a relaxation time ranging from 200 to 600 ms; and (3) pore diameters ranging from 4 µm to greater than 10 µm with very high relaxation time greater than 900 ms, in which unimodal intercrystalline and moldic pores were observed.

The pore size distribution in the low reservoir quality samples derived from the NMR (T_2) distribution curves had unimodal intercrystalline pores that have T_2 close to 200 ms, isolated moldic pores having T_2 greater than 900 ms, and bimodal intercrystalline and moldic pores, while high reservoir quality samples had unimodal intercrystalline pores and bimodal intercrystalline pores, and moldic pores were inferred from the pore size distributions. A positive correlation has been established for samples exhibiting intercrystalline micropores, intercrystalline mesopores, moldic and vuggy mesopores using both the helium porosimeter gas expansion and NMR techniques. The petrophysical behaviour of the carbonate rock units of the Euphrates and Jeribe formations in this study can be considered to be an important tool for identifying and characterising the wide variations of carbonate reservoir heterogeneity at different scales. Pore size categories (2) and (3) show moderate to good reservoir quality, while pore size category (1) represents non-reservoir rock.

1 INTRODUCTION

The main focus of this petrographical and petrophysical study was to conduct an integrated analysis of pore system geometry and pore throat size to understand controls on the initial and residual fluid flow and fluid distribution through heterogeneous carbonate reservoirs. Reservoir rocks are ideally characterized by large pores and pore throat sizes that hold and transport sufficient quantities of hydrocarbons (Ahr, 2008). However, pore throats in tight rocks are small and provide very low permeability. Pore throat connectivities are sensitive to being enhanced or reduced by diagenetic processes such as dissolution or cementation.

Recent studies have used a variety of petrophysical methods to explore the relationships between porosity and permeability in tight reservoirs. For example, Rashid et al. (2015a) and Rashid et al. (2017) investigated pore network systems in tight carbonate formations which are largely controlled by chemical diagenetic processes and tectonic fractures which enhance pore network connectivity and reservoir permeability.

Defining pore systems and the microstructure of carbonate reservoirs have been carried out by Brigaud et al. (2014), Regnet et al. (2014) and Kaczmarek et al. (2015), and some use Nuclear Magnetic Resonance (NMR) to provide pore size distributions in the reservoir samples (Akbar et al., 2000; Westphal et al., 2005). Many of these studies seek to address problems within NMR signals in carbonate reservoirs (e.g., Brigaud et al., 2014; Rashid et al., 2017) while others focus specifically on chalk reservoir pore systems (Li et al., 2014; Megawati et al., 2012) using a wide range of outcrop chalk samples, including tight chalks. Gomord et al. (2016) has developed comparisons between porosity, permeability, MICP, petrography and SEM analysis based on a petrographical study and petrophysical measurements, while Rashid et al. (2015a; b; 2017) also relate porosity, permeability and pore throat size.

The objective of this work is to determine a representative model of large and small pore sizes in examples of porous and tight carbonate reservoirs respectively. This will be achieved by developing a pore size distribution model that compares image analysis with NMR T_2 distribution to present a comparison between pore size in microns (μm) and T_2 in milliseconds (ms) in a suite of both porous and tight carbonates.

2 MATERIAL AND METHODS

Laboratory measurement of porosity, permeability, resistivity (AC frequency=1 kHz, voltage=1V), NMR spectra and capillary pressure curves were conducted on Lower Miocene carbonate reservoir samples from the Euphrates and Jeribe formations (Hussein et al., 2017). A total of 62 core samples were subjected to Soxhlet core cleaning. The cleaned core plugs were then saturated with synthetic formation brine in a core holder under 1000 psi. In addition, 396 sets of porosity and permeability data that were measured by the North Oil Company (NOC) have also been analyzed. Figure 1 shows the study area from which all the data and cores were obtained and Table 1 summarizes the well names. All samples had nominal diameters of 2.54 cm (1 inch) and lengths varying between 2.54 cm to 5.08 cm (1 inch to 2 inches).

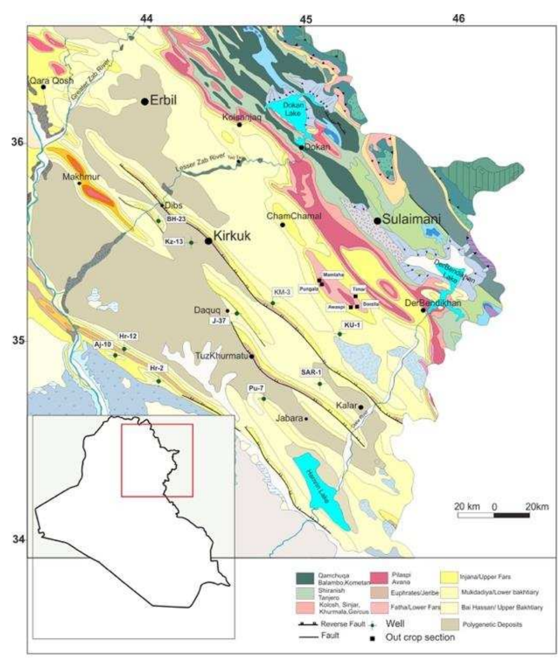

Figure 1. Geological map of Kurdistan region and north east of Iraq shows the selected fields, blocks and outcrop section of the study area, modified from (Sissakian et al., 2000). Well numbers refer to Table 1.

Table 1. Number of core plugs in the Euphrates and Jeribe Formations from studied wells (Figure 1). ϕ porosity; *k* permeability.

Wells	No. of cores (Euphrates Fm.)	No. of cores (Jeribe Fm.)	No. of data from NOC (Euphrates Fm.)	No. of data from NOC (Jeribe Fm.)
HR-2	5	16	131 (ϕ and k)	23 (ϕ only)
BH-23	-	2	-	
PU-7	3	-	-	
JM-37	6	-		46 (ϕ only)
KM-3	3	9	79 (ϕ only)	17 (ϕ and k)
Outcrops	9	7	-	-

3 RESULTS AND DISCUSSION

3.1 Existing classification systems

Carbonate reservoir quality and fluid-flow capacity are determined by their lithology and porosity distribution. Average porosity, porosity type, pore throat size distribution and their spatial distribution are all important in estimating productivity and in the simulation of carbonate reservoirs (Zadeh and Adabi, 2010). Porosity classification includes assessment of pore space characteristics, pore space relationships and porosity evolution controls. A number of different classifications have been developed (Table 2).

Table 2: The most widely used porosity classifications in carbonate rocks.

Porosity classification	Main porosity types
Lonoy (2006) revised classification based on Choquette and Pray (1970) with components from Lucia (1983)	• Micropores (10-50 µm), • Mesopores (50-100 µm), • Macropores (>100 µm), • Intercrystalline micropores (10-20 µm), mesopores (20-60 µm) and intercrystalline macropores (>60 µm). • Interparticle moldic micropores and macropores (10-20 µm >20-30 µm), • Vuggy and mudstone microporosity with micropores of <10 µm
Choquette-Pray (1970) depositional and diagenetic classification	• Fabric selective, • Non-fabric selective • Fabric selective or not
Ahr (2008) generic carbonate porosity classification.	• Depositional setting • Diagenetic process • Mechanical fractures

3.2 Results

It was observed that relaxation time distributions (T_2) of the NMR data were correlated with the pore size distributions derived from the image analysis. Pore diameters smaller than 1 µm were associated with short relaxation times equal to or smaller than 200 ms, while pore diameters ranging from 1 µm to 4 µm provided T_2 values ranging from 200 to 600 ms. Very high relaxation times were observed for pores having pore diameters greater than 10 µm, usually greater than 900 ms. Figure 2 shows 3 typical samples from each pore diameter type.

Porosity evolution and porosity type were identified in these heterogeneous carbonate formations by petrographical examination of the thin section samples, scanning electron microscope and core analysis (Mercury Injection Capillary Pressure test and the NMR pore size distribution). In the tight samples intercrystalline mesopores and isolated moldic microspores indicate unimodal intercrystalline pores with T2 close to 100 ms, while intercrystalline pores greater than 1 µm having T2 greater than 200ms were identified in the tight samples (Figure 3A). Intercrystalline micropores and intercrystalline mesopores, moldic and vuggy micropores were observed from the higher porosity samples studied (Figure 3B and 3C). Hence both Choquette-Pray's (1970) fabric selective and non-fabric selective types could be recognized.

Diagenetic and depositional porosity influences were also recognized. Diagenetic influence emerged in two forms:

1. The pore size distribution in the tight samples derived from the NMR (T2) distribution curves provided unimodal intercrystalline pores that have T2 values close to 200 ms (Figure 3A), while samples with isolated moldic pores showed a bimodal distribution of T2 due to the presence of moldic pores in an intercrystalline matrix, and T2 values ranging from 200 to 600 ms (Figure 3B).
2. In the porous samples, unimodal intercrystalline and moldic pores were observed. The intercrystalline pores have micropore and mesopore sizes, and the moldic and vuggy pores have a mesopore size range throughout the high porosity of the data set (Figure 3C).

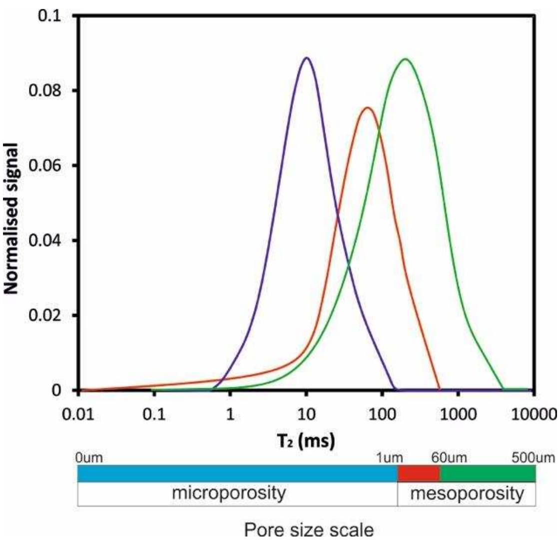

Figure 2. Typical transgressive relaxation time distribution (T_2) curves calibrated with pore diameters which have been obtained from image analysis; they are used as a standard scale in this study, distinguishing microporosity from mesoporosity.

Three types of pores including microporous intercrystalline pores, mesopores, and isolated moldic or vuggy pores were recorded in the tight samples. During diagenesis the intercrystalline pore type's size increases to mesopore size throughout the porous samples. Further diagenesis leads to the formation of moldic and vuggy pores which then occur in a matrix characterized by inter-connected mesopores. The heterogeneous distribution of pore structure throughout the study area was not only influenced by the pore size, and pore size distribution, but by the pore throat size, all of which was found to vary throughout the study area.

Pore throat heterogeneity is thought to control the fluid flow conductivity and the reservoir potential throughout the study area (Rashid et al., 2017). The microporous and mesoporous pore system is interconnected by pore throats smaller than 0.5±0.07 μm in the nanoporous and microporous pore throat sizes of the tight samples including both Euphrates and Jeribe samples (Figure 4). The mesoporous pore spaces are connected by pore throats greater than 0.5±0.7 μm that are characterized by mesoporous pore throat radii and mesoporous and macroporous pore throat sizes in the porous part of the area. The small pore throat sizes encountered in the tight samples ensure that the rock porosity is low, pore connectivity is low and consequently permeability and reservoir potential is low.

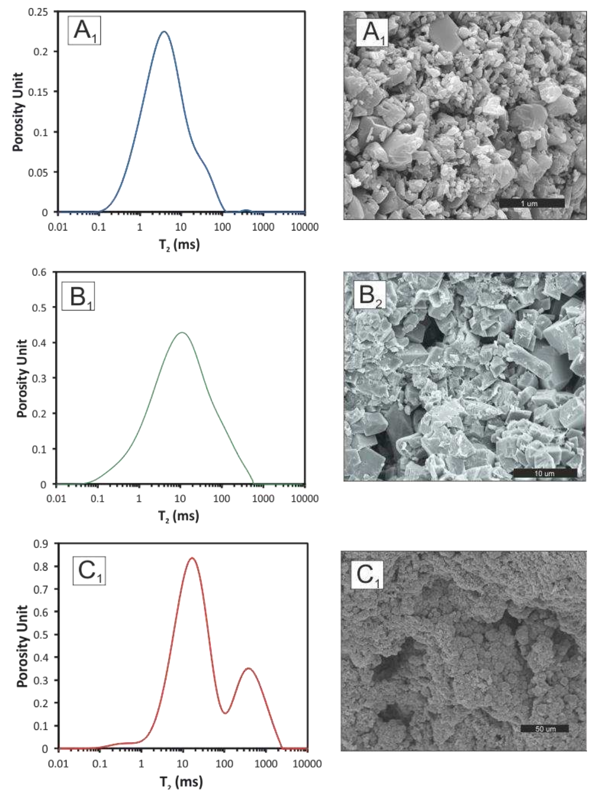

Figure 3. NMR relaxation time (T2) in the tight samples of the study area: (A) Intercrystalline pore diameters smaller than 1 μm (T2 < 200 ms), (B): Moldic pores with diameters greater than 60 μm (T2>900 ms). C) Intercrystalline pore diameters smaller than 1 μm and moldic pores with diameters greater than 71.82 μm.

By contrast, the moldic and vuggy post depositional pores throughout the porous data set form a well-interconnected network and enhance the reservoir potential. Cement, which is diagenetic product, has blocked pore throat spaces, and an average pore throat size of 0.41±0.07 μm was recorded for the tight samples. However, dolomitization and dissolution increased pore connectivity and pore throat sizes. Porous samples have a minimum pore throat radius of 0.50±0.7 μm with an average of 2.25±0.7 μm, and a good reservoir potential is preserved in the porous samples of the study area (Figure 4).

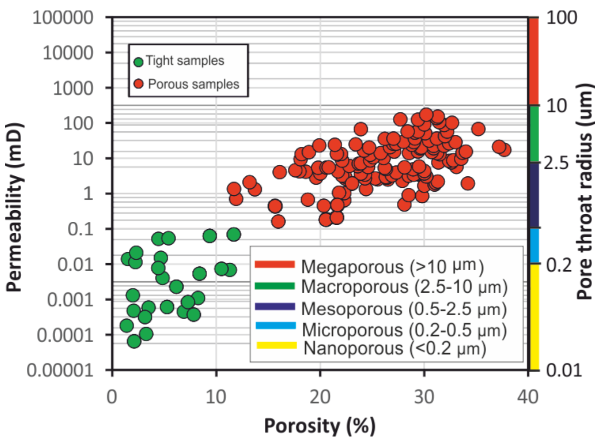

Figure 4. Poroperm cross-plot for 171 samples using measured helium porosity, Klinkenberg-corrected helium permeability and image analysis/MICP-derived pore throat size. The pore throats have nanoporous and microporous sizes in the 'tight' data (green symbols) while the pore throat sizes are enlarged to mesoporous and macroporous in the enhanced porosity data (red symbols).

4 CONCLUSION

Based on the pore size distributions in the heterogeneous carbonate reservoirs of the Euphrates and Jeribe formations of North Iraq, three rock-types have been identified:

Rock-type I represents a non-reservoir rock facies and occurs in the tight part of the Euphrates and Jeribe formations throughout the study area. The pore size distributions of this rock-type which are derived from the image analysis and NMR T_2 distribution curves are uni-modal and have a mean T_2 value smaller than 200 ms. However, some samples have pore sizes of up to 2 µm, which also affects the shape of their NMR distribution curves, and can be observed on SEM images.

Rock-type II is characterised by bimodal pore size, pore throat size and NMR distributions. The intercrystalline microporosity has a mean T_2 value similar for the first group, but the mesoscale pores are characterized by very high mean relaxation times which may exceeded 900 ms, the pore type is composed of intercrystalline, moldic porosity and vugs with sizes identified as mesoporosity. The moldic and vuggy pore diameters range between 10±0.68µm and 349±0.68 µm with an arithmetic mean of 72±0.68 µm.

Rock-type III is characterized by a unimodal normalised NMR T_2 distribution, with a modal pore radius greater than 200 ms. In addition, image analysis shows a homogeneous pore radius distribution. The pore type of this rock type consisted of moldic and vuggy mesopores, the pore diameter ranged between 2±0.62 µm to 65±0.62 µm with an average of 20±0.62 µm. The rock texture and pore system of this petrophysical rock type is affected by dolomitization diagenesis that enhanced the reservoir quality, especially porosity. This rock type would be expected to have reservoir potential from both the matrix porosity and from its natural fractures.

In summary, in the Jeribe and Euphrates formations rock-types **II** and **III** are identified as potential reservoir rocks. Productive reservoir units of these types are found throughout the western part of the study area in this study. By contrast, Rock-type **I** has no reservoir quality.

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