CHARACTERISTICS OF CARBONATE ROCK TYPES IN THE MIDDLE EAST

Moustafa Dernaika, Bashar Mansour, Osama Al Jallad, Ingrain – Halliburton, Abu Dhabi

This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Trondheim, Norway, 27-30 August 2018

ABSTRACT
The complexity of carbonate reservoirs necessitates having a consistent approach in defining rock types. Core data on a rock-type basis is required as input for modelling reservoir performance. The objective of this paper is to evaluate carbonate rock types based on porosity (type), permeability, capillary pressure, textural facies and diagenesis.

Over 1000 core plugs were studied from 7 different carbonate reservoirs across the Middle East region. The plugs were carefully selected to represent main property variations in the cored intervals. The data set available included laboratory-measured helium porosity, gas permeability, thin-sections and high-pressure mercury injection. Plug-scale X-ray CT imaging was acquired to ensure the samples were free of induced fractures and other anomalies that can affect the permeability measurements. Rock textures/facies were analyzed in the thin-section photomicrographs and were classified based on their content as grainy, muddy and mixed. Special attention was given to the diagenesis effects mainly compaction, cementation and dissolution. Porosity was defined as interparticle, intercrystalline, moldic, intraparticle or vuggy.

The texture information was plotted in the porosity-permeability domain, and was found to produce three distinct porosity-permeability relationships. Each texture gave unique poro-perm trend. Rock types were defined on the poroperm trends, and showed strong link to the capillary pressure. For each poroperm trend, the rock types were distinguished by detailed Dunham textures and different degrees of diagenesis. Detailed textures and diagenesis were correlated reasonably well with the poroperm data and MICP.

A new rock typing approach is presented in this research study. Carbonate rock types were successfully classified based on rock porosity, permeability, capillarity and textural facies. Conclusive porosity-permeability relationships were obtained from textural rock properties and diagenesis, which were linked to rock types using Pc and PTSD curves. The texture-diagenesis based rock types provide more insight into the effects of geology on fluid flow and saturation. Geological textures/facies can be derived along cored intervals, which give upscaling options for permeability and rock types in the reservoir.

INTRODUCTION
Reservoir rock types (RRT) can be defined based on combined petrophysical properties and geological descriptions [1]. The petrophysical properties may include measurements

from porosity, permeability as well as mercury-derived drainage capillary pressure (Pc) and pore-throat size distribution (PTSD) curves. Geological descriptions are normally obtained from thin-section photomicrograph analysis, which aim at defining pore systems, textures, facies, diagenesis and depositional environment. In carbonates, it may not be straightforward to establish reservoir rock types due to reservoir heterogeneity. The rock types may not be sharply distinguished but broadly delineated and possibly overlapping, and hence sorted by their common characteristics or traits.

To achieve unique rock types, carbonate rocks should be classified based on their contents and pore geometries. The content can be revealed from rock micro-structure (texture), which can be described from the thin-section photomicrographs. Carbonate micro-structures may be classified as grainy, muddy or mixed [2]. Grainy carbonate contains grains only. Muddy carbonate contains matrix only (mud). Mixed carbonate contains both grains and matrix. In all the three classes, the effects of dissolution, cementation and compaction (i.e. diagenesis) should be considered. In this perspective the Dunham [3] textural classification of grainstone, rudstone and boundstone, for instance, would fall into the grainy class, while the mudstone and wackstone would fall into the muddy classification. Packstones and floatstones would then fall into the mixed texture category. On the other hand, the pore geometry could be defined based on porosity (pore) type and pore-throat size distribution (PTSD). The porosity type could be interparticle, intraparticle, intercrystalline, moldic or vuggy. A heterogeneous reservoir rock may have more than one of these pore types. The PTSD curve can be obtained from high-pressure mercury injection (MICP) experiments and can be used to enhance the description of the rock types by assigning cut-offs for porosity and pore-throat sizes for similar facies.

In our previous study [4], helium porosity and gas permeability data were fitted into three unique trends. The different trends were established based on the different textures whereas the extent of the trend was controlled by diagenesis processes (e.g. cementation, compaction and dissolution).

In this research, we studied the rock types of the samples within each texture (poroperm) trend. The rock types (along each poroperm trend) were identified based on the link between the sample detailed Dunham texture, diagenesis and capillary pressure.

ROCK TYPING APPROACH

Figure 1 gives an overview of the rock typing approach followed in this work.

Plug-Scale X-Ray CT

The samples (1.5” diameter plugs) were first cleaned with hot solvents in soxhlet for helium porosity and gas permeability measurements. Then they were imaged by Dual-Energy X-ray CT scanning to ensure the samples are free of induced fractures and other anomalies that may affect the permeability data. Without the plug-scale CT image it will not be possible to obtain conclusive poroperm trends based on textures. Dernaika et al [5] studied the effects of fractured samples on the porosity-permeability relationships, and showed how mud-dominated samples can yield permeabilities higher than the true values by several orders of magnitude. The CT images were also used to select representative thin-section and MICP trims. This is a crucial requirement in heterogeneous reservoirs where heterogeneity can have dramatic effects at the centimeter scale. Figure 2 is an example of this case where a color-scale plug CT image is shown in the middle with two end trims. The plug porosity and permeability are 20% and 1mD, respectively. End trim 1 gave very different geological and petrophysical data in comparison with the data from end trim 2. This is demonstrated with the acquired thin-section photomicrographs and mercury-derived poroperm data and PTSD curves. This analysis shows the importance of the plug-level CT images for acquiring representative measurements.

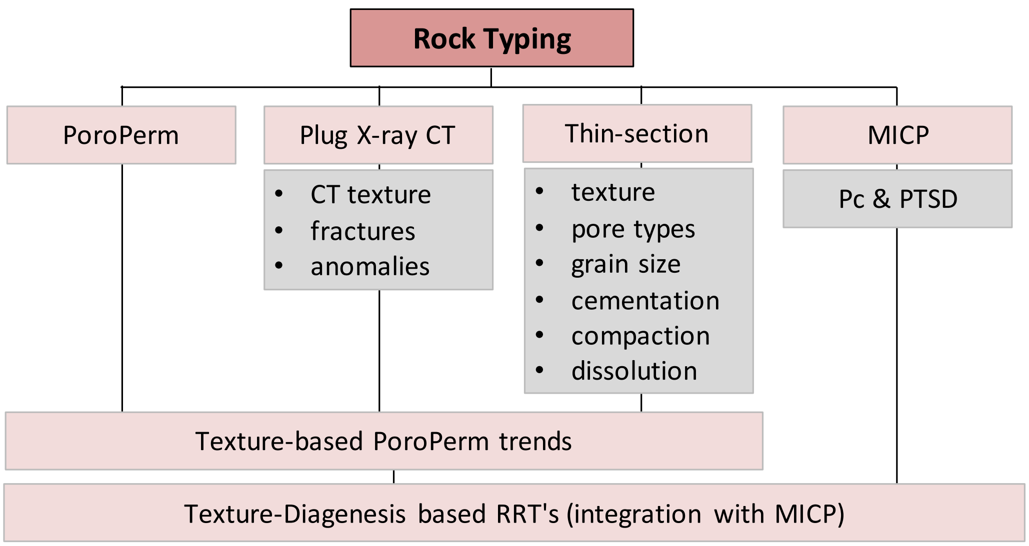

Figure 1 Workflow of the Rock Typing approach followed in this study

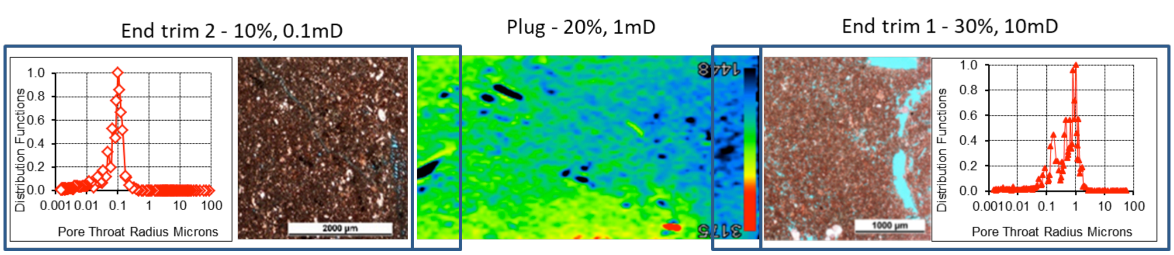

Figure 2 In the middle is shown a color-scale plug CT image with 20% porosity and 1mD. End trim 1 was cut from the right end of the plug and gave very different geological and petrophysical data from the end trim 2, which was cut from the left side. This shows the importance of the plug CT image.

Texture-Based Porosity-Permeability Trends

The key step in rock typing is the classification of the porosity-permeability data based on textures. In [4], we demonstrated how the samples could be grouped in three different poroperm trends under grainy, mixed and muddy textures. Figure 3 depicts the texture-based poroperm trends for all the representative samples from all the seven reservoirs.

The plugs were selected using a well-established statistical sample selection procedure based on high-resolution dual energy CT imaging and CT textural analysis [5,7,8]. Detailed analysis was given on the effects of textures on fluid flow with emphasis on the effects of diagenesis on the variation of porosity and permeability within each trend. Figure 4 depicts the conceptual model of the porosity-permeability relationship with texture. It is important to realize that as we move from the muddy texture to the grainy texture (at the same porosity), permeability and grain size increase; whereas micrite content and surface area decrease. It is also normally true that (at the same porosity) and as we move from the muddy to the grainy texture the pore size increases while the number of pores decreases. These variations in textures and the resultant pore system would have direct effects on the flow characteristics and capillarity in the reservoir. In grainy samples the medium of flow is between grains while in the muddy samples the flow occurs in the mud. In mixed texture samples the flow occurs between the grains and in the mud.

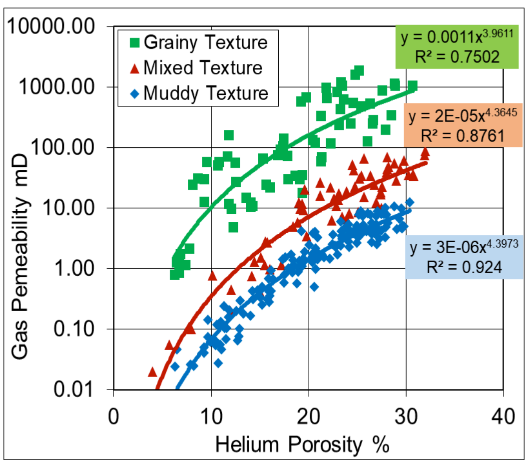

Figure 3 Texture-based poroperm trends for all samples in the seven different reservoirs

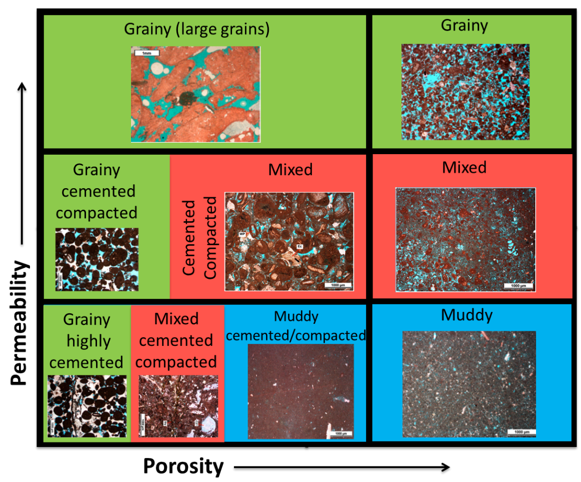

Figure 4 Texture-Diagenesis PoroPerm Diagram

Integration with MICP

Figure 5 shows examples from the effects of texture on Pc and PTSD curves. The texture effect is given for high porosity (around 25%) and low porosity (around 10%) samples (different diagenesis: here cementation). There is almost one order of magnitude difference between the different textures at the same porosity. The grainy samples are characterised by larger pore throat size, lower entry pressure and higher permeability. Initial water saturation (Swi) may not always be linked to permeability or texture in carbonates. It is dependent on the Pc level as well as the percentage of the smallest pores in the rocks [6]. In figure 5, for instance, the high-porosity muddy samples have lower Swi values (at high Pc) compared to the grainy and mixed texture samples because the mixed and grainy samples have more pore-throat fractions below 0.1micron as can be seen in the corresponding PTSD plots. Figure 6 shows the effect of porosity (diagenesis) on the Pc and PTSD curves for each texture. These plots demonstrate the influence of texture and diagenesis on petrophysical properties, hence confirming the importance of texture as a fundamental tool for rock typing.

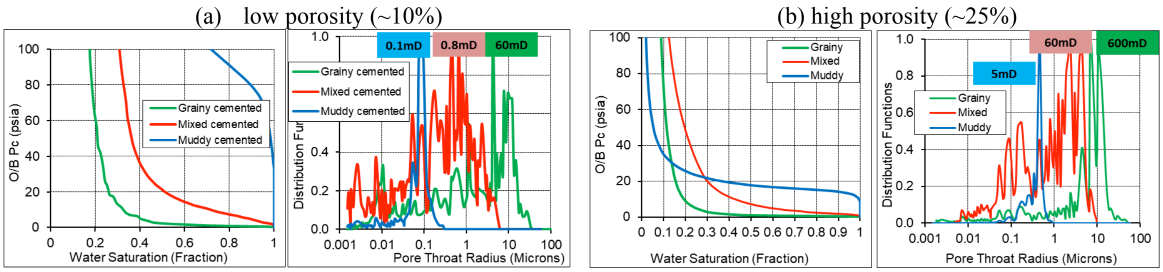

Figure 5 Effect of texture (depositional environment) on Pc and PTSD (a) at low porosity and (b) at high porosity

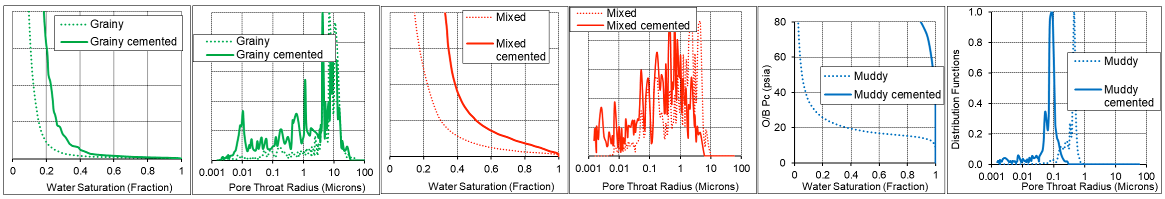

Figure 6 Effect of porosity (diagenesis) on the Pc and PTSD curves for the three textures

CARBONATE ROCK TYPES

The rock types were established along the main texture (poroperm) trends: grainy, mixed and muddy. The rock types were identified based on detailed Dunham textures and different diagenesis processes (e.g. leaching, cementation, compaction). The different rock types were correlated reasonably well with the poroperm data and the MICP-derived Pc & PTSD curves. Figure 7 to figure 12 give the summary of the main rock type characteristics found in the seven carbonate reservoirs under study. Each figure shows all the rock types within single Dunham texture classification along with their poroperm data and representative Pc & PTSD curves in addition to a representative thin-section photomicrograph from each rock type group. The Pc curves are plotted in a semi-log format to show the capillarity behavior clearly. The mercury-derived Pc was converted to oil-water fluid system using interfacial tension of 32 mN/m and contact angle of 30 degrees. The thin-section photomicrographs are shown in the same order as given in the legend of the figures. Within each rock type, all samples show consistent MICP and thin-section information but we only show single representative data to avoid crowd plots.

Figure 7 and figure 8 show the grainy limestone rock types from grainstone and Rudstone textures, respectively. In figure 7, there are 3 grainstone rock types with different degrees of cementation. The poroperm data are plotted with the main grainy trend and show higher values than the average trend. The presence of cement largely affected the poroperm characteristics and the corresponding Pc & PTSD curves. It is seen that the percentage of microporosity increases with cementation. The microporoity in these rock types is coming from micritization in the grains. In figure 8, five rock types were identified, mainly from the Rudstone texture. The rock types show very heterogeneous PTSD curves due to large variations in grain sizes and pore sizes with different diagenetic footprints such as leaching and cementation. The best quality rock is the rudstone-to-boundstone texture while the poorest quality rock is the cemented rudstone. Two rock types were seen from the rud/bound-to-floatstone with higher percentage of floatstone in the rud/bound to floatstone 2 as labelled in the corresponding legend in the figure. One more rock type was seen in this group, which is the rud-to-grainstone texture with intraparticle porosity. The rud-to-boundstone RRT show a main PTSD peak at around 100microns (~1000mD). The cemented rudstone rock type gives wide PTSD, while the rest of the rock types show bimodal PTSD.

Figure 9 gives 4 dolomitic RRT's with different degrees of leaching and compaction. The poroperm data are seen lower than the average grainy trend. The rock types show narrow and uniform PTSD curves.

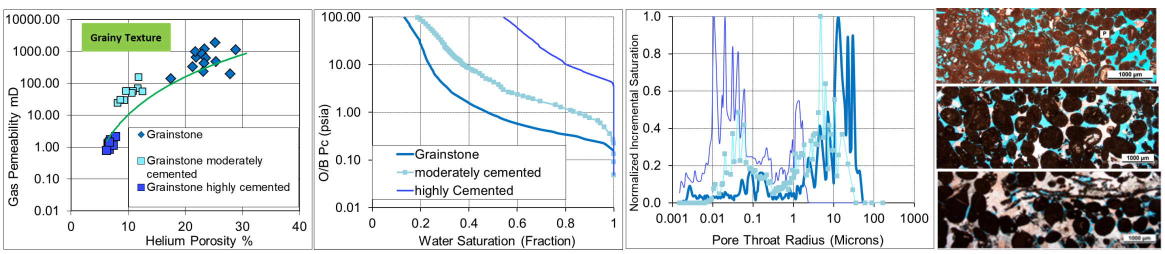

Figure 7 Grainstone 3 RRT's: representative MICP curves and thin-section photomicrograph are given for each RRT

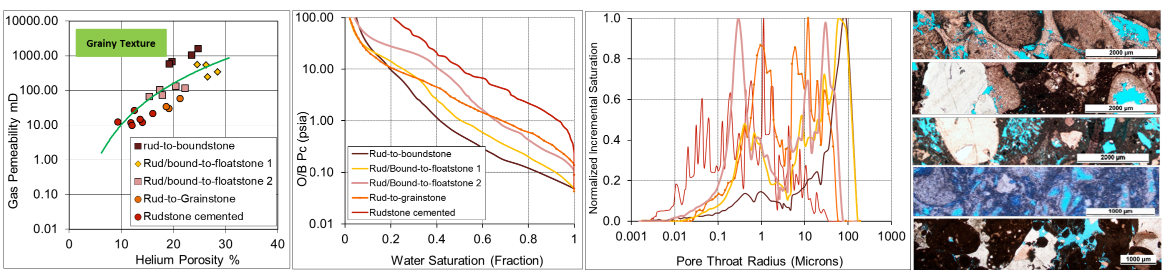

Figure 8 Rudstone 5 RRT's: representative MICP curves and thin-section photomicrograph are given for each RRT

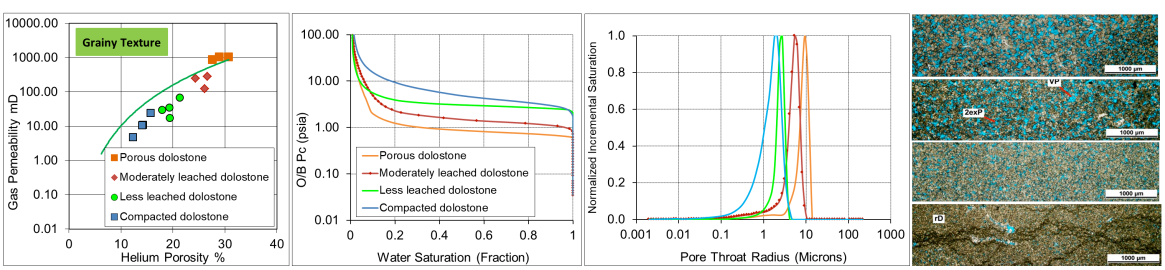

Figure 9 Dolomitic 4 RRT's: representative MICP curves and thin-section photomicrograph are given for each RRT

Figure 10 and figure 11 show the mixed limestone rock types from packstone and floatstone textures, respectively. In figure 10, there are 5 packstone rock types with different degrees of leaching, compaction and cementation. The poroperm data are plotted with the main mixed trend. The presence of cement and compaction largely affected the poroperm characteristics and the corresponding Pc & PTSD curves. Samples with less compaction/cementation (i.e. >1mD) show heterogeneous PTSD.

In figure 11, three rock types were identified, mainly from the Floatstone texture. The main difference in those rock types is related to detailed textural facies with floatstone-to-boundstone being the best quality with highest permeability range and lowest Pc entry pressure. The least quality rock type is the bioturbated floatstone-to-packstone texture. The samples show the main PTSD peak less than 1micron. The tendency towards larger pore throats is caused due to leaching and presence of boundstone texture.

Figure 12 depicts 5 rock types from the wackstone/mudstone textures. The poroperm data and Pc curves are largely influenced by cementation, recrystallization and compaction. All the samples have permeability less than 10mD, Pc entry pressure above 10psi (oil-water) and pore-throat radius below 1micron.

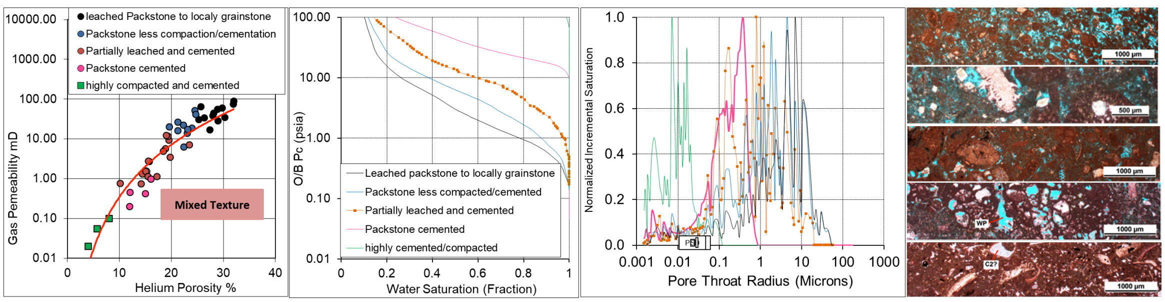

Figure 10 Packstone 5 RRT's: representative MICP curves and thin-section photomicrograph are given for each RRT

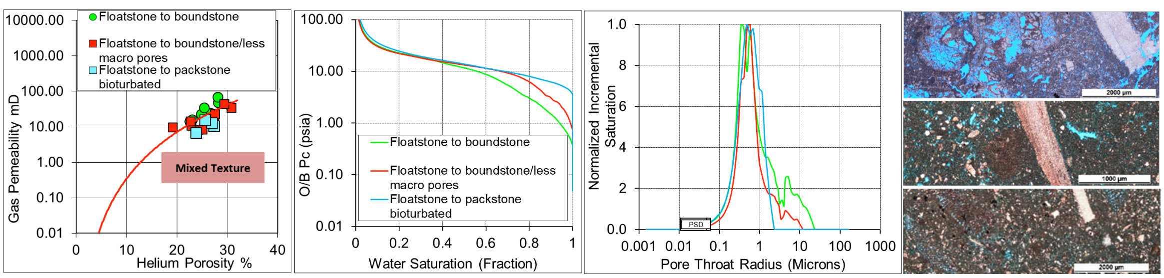

Figure 11 Floatstone 3 RRT's: representative MICP curves and thin-section photomicrograph are given for each RRT

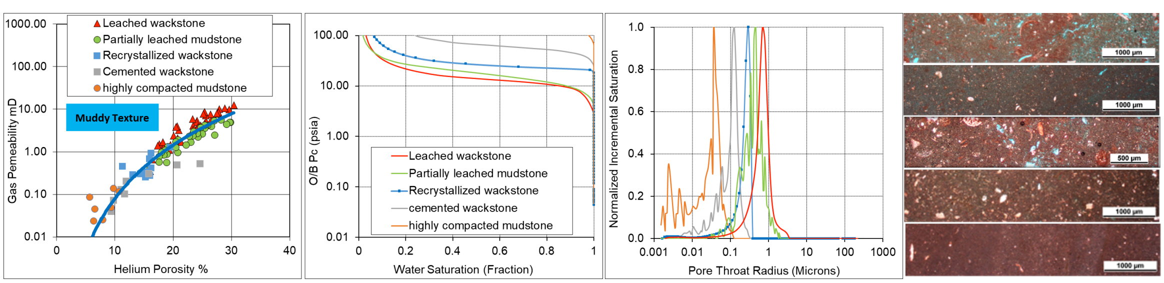

Figure 12 Wackstone/mudstone 5 RRT's: representative MICP curves and thin-section are given for each RRT

Table below gives summary of the 25 rock type characteristics derived in this study.

RRT	Texture/Diagenesis	Porosity (%)	Permeability (mD)	PTSD (microns)	Entry Pc (o-w psi)	Swi@100psi (%)
Grainy Texture						
1	Grainstone	20-30	100-1000	15	0.35	10-15
2	Grainstone moderately cemented	8-12	25-100	5, 0.5	1	20
3	Grainstone highly cemented	5	1	1, 0.02	10	50
4	Rud-boundstone	20-25	1000	100	0.10	5
5	Rud/bound to float1	25	350	100, 0.5	0.2	5
6	Rud/bound to float2	15-22	100	30, 0.3	0.5	5
7	Rud to grainstone	20	35	12, 1	0.6	5
8	Cemented rudstone	9-16	15	10-0.01	2	20
9	Porous dolostone	30	1000	10	0.7	2
10	Leached dolostone	25	200	5	1	2
11	Less leached dolostone	20	35	3	2.5	2
12	Compacted dolostone	15	10	1	3.5	2
Mixed Texture						
13	Leached packstone	25-32	30-90	20-0.1	1	12
14	Less compacted packstone	20-25	10-20	20-0.1	2	12
15	Partially leached packstone	15-20	1-10	10-0.1	5	15
16	Cemented packstone	12-16	0.2-1	1-0.01	20	25
17	Highly cemented packstone	4-8	0.02-0.1	0.02, 0.003	100	100
18	Float-to-boundstone	22-28	20-70	5, 0.5	3	2
19	Float to bound less leached	20-30	20-40	4, 0.5	5	2
20	Bioturbated float-to-packstone	25	15	0.5	8	2
Muddy Texture						
21	Leached wackstone	20-30	1-10	0.7	10	2
22	Partially leached mudstone	20-30	1-10	0.5	10	2
23	Recrystallized wackstone	13-16	0.3-0.9	0.3	25	8
24	Cemented wackstone	10-15	0.05-0.3	0.1	50	25
25	Highly compacted mudstone	5-10	0.03-0.1	0.04	100	100

SUMMARY AND CONCLUSIONS

Plug samples were analysed from seven different carbonate reservoirs in the Middle East. The samples were selected from the cored intervals by statistical methods. The core plugs were thoroughly analysed to ensure they were free of induced fractures and other anomalies which may affect the laboratory measurements. The sample's textures were classified from thin-section photomicrographs and were plotted in the porosity-permeability domain. The rock types were identified based on detailed Dunham textures and diagenesis. The following can be concluded from the results in this study,

1. Three different textures (grainy, muddy & mixed) were identified in the reservoirs.
2. Distinct porosity-permeability trends were obtained for the different textures.
3. The extent of the trends was controlled by diagenesis (i.e. compaction, cementation, and dissolution).
4. The different rock textures gave distinct Pc and PTSD curves.
5. Clear effects from diagenesis were seen on the Pc and PTSD curves

6. Detailed Dunham textures and diagenesis were correlated reasonably well with MICP and poroperm
7. A total of 12 RRT's were derived from the grainy texture: 3 RRT's from grainstone and 5 RRT's from Rudstone
8. A total of 8 RRT's were obtained from the mixed texture: 5 RRT's from the packstone texture and 3 RRT's from the floatstone texture
9. A total of 5 RRT's were identified from the muddy texture: 3 RRT's from the wackstone texture and 2 RRT's from the mudstone texture.

ACKNOWLEDGEMENTS

The authors wish to acknowledge Halliburton management for the permission to publish the results of this research study.

REFERENCES

1. Masalmeh, S.K. and Jing, X.D. (2007) "Improved Characterization and Modelling of Carbonate Reservoirs for Predicting Waterflood Performance", paper IPTC 11722 presented at the International Petroleum Technology.
2. Mousavi, M., Prodanovic, M. and Jacobi, D.: "New Classification of Carbonate Rocks for Process-Based Pore-Scale Modeling", SPE Journal (April 2013), SPE 163073.
3. Dunham R.J. 1962. Classification of Carbonate Rocks According to Depositional Texture. In Classification of Carbonate Rocks: A Symposium. American Association of Petroleum Geologists Memoir 1, ed. W.E. Ham, 108-121. Tulsa, Oklahoma: AAPG.
4. Dernaika, M.R. and Sinclair, G.G. (2017) "Resolving the Link between Porosity and Permeability in Carbonate Pore Systems" paper SCA2017-77 presented at the International Symposium of the Society of Core Analysts held in Vienna, Austria, 27-30 August 2017
5. Dernaika, M.R., Mansour, B., Gonzalez, D., Koronfol, S., Mahgoub, F., Al Jallad, O., Contreras, M. (2017) "Upscaled Permeability and Rock Types in a Heterogeneous Carbonate Core from the Middle East" SPE-185991-MS, presented at the SPE Reservoir Characterisation and Simulation Conference and Exhibition held in Abu Dhabi, UAE, 8—10 May
6. Serag El Din, S., Dernaika, M.R., Kalam, M.Z. and Hannon, L., (2013): "The Effect of Rock Properties on Residual Oil Saturation in Heterogeneous Carbonate Rocks", paper SPE 164141 presented at the SPE Middle East Oil and Gas Show and Exhibition that will be held in Manama, Bahrain, 10–13 March.
7. Dernaika, M. R., Naseer Uddin, Y., Koronfol, S., Al Jallad, O., Sinclair, G., (2015) "Multi-Scale Rock Analysis for Improved Characterization of Complex Carbonates" SCA2015 paper presented at the International Symposium of the Society of Core Analysts held in St. John's, Newfoundland and Labrador, Canada, 16-21 August.
8. Al-Owihan, H., Al-Wadi, M., Thakur, S., Behbehani, S., Al-Jabari, N., Dernaika, M. and Koronfol, S., (2014), "Advanced Rock Characterization by Dual-Energy CT Imaging: A Novel Method for Complex Reservoir Evaluation" paper IPTC 17625 presented at the International Petroleum Technology Conference held in Doha, Qatar, 20–22 January.