DOES THE PORE CLASS CONCEPT FOR CARBONATES MAKE SENSE FOR MULTIPHASE FLOW?

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ABSTRACT

Different carbonate pore classes show large variation in petrophysics properties as well as in single- and two-phase flow properties. A few attempts have been recorded in the past to find correlation between petro-physics parameters and pore classes. Results showed that this approach gives improved correlations between porosity and permeability. However, the extension of the concept to integration of basic petrophysics properties and multiphase flow has not yet been extensively investigated. This paper represents an attempt to apply the pore class concept to multiphase flow properties.

In order to address this issue, carbonate samples have been grouped into different pore classes, like intercrystalline, interparticle, moldic, and chalk material, with its subset of grouping for macro-, meso- or micro-porosity and further split into homogeneous or more heterogeneous / patchy material, all based on thin section analysis and porosity-permeability cross plots.

The cores representing different carbonate pore classes have earlier been used to measure both petrophysical parameters such as porosity, permeability, electrical properties, derived tortuosities, dispersion, and capillary pressure and pore size distribution. These results formed the background for the current multiphase flow analysis by water flooding.

The results have shown that grouping carbonates with respect to different pore classes improves correlations between some of the petrophysics properties and oil recovery efficiency by waterflooding

INTRODUCTION

Carbonate reservoir rocks are heterogeneous due to deposition of different pore types and therefore reserve estimation is not predictable with certainty. Recovery efficiency in carbonate reservoirs is also a challenge due to variety in fluid flow properties.

The first step to simplify heterogonous carbonates was taken by Archie (1952) to classify carbonates based on their visual pore sizes, and link these to the petrophysical properties. Another classification developed by Choqutte and Pray (1970) relates different carbonate pore types to depositional environments but it is difficult to correlate these with fluid flow properties. Later, Lucia (1983) applied the concept of rock fabric and flow unit, and tried to relate different carbonate pore systems to petropyhysical properties. The classification by Lucia (1983) predicts a systematic relationship between permeability and porosity, and estimation of the water saturation for the interparticle porosities. Later Wang et al. (1994, 1996) implemented the concept of flow unit to improve the prediction of the flow performance by simulation in shallow-water carbonate reservoirs and also a carbonate ramp reservoir.

Lonoy (2006) introduced a new scheme to classify carbonate pore types based on key elements used by Choqutte and Pray (1970) and Lucia (1983).

The new classification by Lonoy (2006) correlates more accurately between permeability and porosity compared to the Lucia (1983) type of classifications. This new classification includes 20 sub-pore classes and divides the genetic pore types introduced by Choqutte and Pray (1970) such as interparticle, intercrysrtalline, and mouldic pore types into patchy and uniform pore distributions. These new pore systems are further subdivided into macro-, meso- and micro-porosity based on the dominating pore sizes. O'Hanlon et al. (1996) describes how that, beside permeability and initial water saturation, lithology appears to be the major controlling parameters on water/oil relative permabilities for a giant carbonate reservoir. Okasha et al. (2003) reported that differences in recovery efficiency and residual oil saturation of two different carbonate reservoirs in Saudi Arabia are related to variation in rock fabric, diagenesis and pore size distribution. Kamath et al. (2001) and Tie et al. (2005) reported variation in residual oil saturation with different capillary numbers for carbonates samples.

A few attempts in the past have recorded the possible correlations between recovery efficiency and basic petrophysical properties. Wardlaw and Cassan (1978) found a correlation between mercury recovery efficiency and pore structure characteristics like coordination numbers and pore-to-throat size ratios of 36 samples. Earlier studies by Skauge et al. (2006) showed a link between waterflood efficiency and single phase flow properties characterized by dispersion experiments.

Recently, Pourmohammadi *et al.* (2007) reported variation in single phase fluid flow properties of different carbonate pore systems from laboratory experiments. The study included eleven pore classes based on the Lonoy (2006) approach. It covered various basic petropyhysical properties and also mixing characteristics in different carbonate porosities such as dispersivity (a measure of mixing length), flowing fraction and dead-end pores.

This study is a continuation of previous work to integrate those results with two phase flow, and have the main focus on waterflood efficiency. The objective is to identify the most important single phase flow properties which may control waterflood efficiency. Further it is discussed whether these single phase properties are sufficient, or if the pore class concept should be included to predict recovery efficiency by water flooding.

Experiments and Analysis Approaches

Material Selection

The test material originates from reservoir formations in the Barents Sea, North Sea and Middle East. 46 plug samples, touching on 9 pure and 2 mixed carbonate pore types in terms of Lonoy's classification, were brought through the entire, or parts of, an extended experimental approach and SCAL program.

The samples were selected among many candidates. Besides distribution among pore types and appearance properties (like homogeneity and consolidation), one selection criteria was to have the permeability and porosity span be as large as possible for each pore type.
Most samples were received at fresh state, and all of them were cleaned before being introduced to the test program. However, wettability measurements showed that not all samples were rendered highly water wet, though only very few would spontaneously imbibe oil.

Experimental Procedures

Test conditions were room temperature and 20 bar net overburden pressure. Test fluids were synthetic sea water (SSW) and decane. Exceptions were made for dispersion tests with 8 bar back pressure; marcol-152 was used when high viscosity oil was needed (*e.g.* in establishing S_{wi}). Prior to testing, all samples were cleaned by warm miscible solvent flooding, and saturated with synthetic sea water.

Formation resistivity factor measurements were performed in a cycle of stepwise increasing and then decreasing confinement pressures. The resistance was fairly stable above 30 bar net overburden pressure, and the reported values were measured at 35 bar.

Dispersion tests were performed by miscibly displace SSW from the pores by a brine solution with slightly higher NaCl-content. The characteristic dispersion profile is estimated directly by continuous on-line conductivity measurement of the effluent. Dispersion tests were performed at $S_w=1$ and S_{or}, and experimental results were simulated to determine both dispersivity and flowing- and dead-end fractions of the pore volume.

Water floorings were performed with constant injection rate, continuous acquisition of differential pressure and oil production. Two bump rates were applied at the end, with maximum differential pressure of 30 bar.

Results and Discussions

Results from experimental work are plotted in Figures 1 to 9.

Waterflooding oil recovery shows a certain pore type grouping. Figure 1 shows that high recovery can be expected from chalk, while mouldic porosity has low recovery. Further, interparticle pore types have intermediate oil recovery, while intercrystalline porosities are scattered concerning recovery. This observation indicates that the pore type concept certainly makes sense for multiphase flow.

Figure 2 shows the primary drainage initial water saturation prior to waterflooding. The majority of the samples have S_{wi} below 25%. Most pore types show a certain span, and the plot indicates that pore type does not have a significant impact on a S_{wi} achieved by primary drainage.

The cross plot of oil recovery vs. formation resistivity factor, FF (Figure 3), shows a negative general trend (all plotted points, without pore type considerations) between these two parameters. The plot shows that chalk samples generally have low FF and high oil recovery. Mouldic macro-porosity samples seem to have high FF and low recovery. Variations in formation resistivity factor for different carbonate pore classes are given in Figure 4. Pourmohammadi *et al.* (2007) showed that formation resistivity factor is correlated to both porosity and permeability.

Dispersivity is the measure of the mixing length, and is related to the degree of the pore connectivity characterized by coordination number. Degree of mixing in different carbonate porosities has already given and discussed by Skauge et al. (2006) and Pourmohammadi *et al.* (2007). Low dispersive porous systems are expected to have a higher degree of pore connectivity, which contributes to better sweep efficiency in two-phase flow. Hence, it is generally expected that recovery efficiency is higher from low dispersive systems.

Figure 5 shows the negative general trend between oil recovery and dispersivity. The trend appears more accurate at lower dispersivity values, but this may be caused by the limited number of points in this region. The plot tells that chalk samples generally have low dispersivity and high oil recovery. Mouldic macro-porosity samples seem to have high dispersivity and low recovery. Figure 6 shows dispersivity distribution to pore types among the tested samples. Similarly as for formation resistivity factor, the chalk samples are grouped at the lower values, the mouldic samples are grouped at the higher values, and most of the rest have values in between, with some pore types spanning the whole region There seem to be a pattern that micro-porosity has low dispersivity.

Flowing fraction, f, is the ratio between flowing pore volume and total pore volume, and is estimated from the dispersion test. Figure 7 indicates that there is a pore type dependent relation between oil recovery and flowing fraction. Our result showed that generally recovery efficiency is more correlated with flowing fraction than the total porosity. The plot shows a positive, quite broad, general trend, and does not appear to be of much help in predicting oil recovery. However, if the flowing fraction for a particular pore type (*e.g.* a chalk sample) is known, oil recovery can be predicted with significantly increased accuracy. The same goes for mouldic samples. These two pore classes seem to form the upper and lower border of the general trend. The other pore types lie in between, with various trend qualities. Pourmohammadi *et al.* (2007) showed how flowing fraction spans relatively wide for the different carbonate pore classes, which is necessary to form trends in the cross-plot against recovery.

Figure 8 shows an even better general correlation between oil recovery and flowing fraction at residual oil saturation. These flowing fraction values, f_{Sor}, are measured at residual oil saturation, and show the ratio of non-dendritic water volume to total pore volume. Figure 8 shows that the pore types do not group, but form trends along similar paths, making a narrow general relation between f_{Sor} and oil recovery. Figure 9 shows scattered flowing fractions at residual oil values for many pore types.

Comparison of Figure 7 and Figure 8 (flowing fraction at 100% water saturation and f_{Sor}, respectively) indicates that the presence of residual oil undermines the pore type dependency in predicting oil recovery as the correlation is stronger between water flood efficiency and flowing fraction at residual. This strong correlation indicates that oil is displaced mostly in the flowing part of carbonate porosities although they have different pore types with variable structures.

Table 1 gives an overview of the pore types' qualitative relations between oil recovery and different properties. Average water flood efficiency for studied carbonate pore classes is also included. The pore size distribution index (PSDI) is derived by NMR measurements, and indicates the degree of sorting (Pourmohammadi *et al.*, 2007), ranging between zero and unity, with unity as a completely homogenous porous medium with no pore size variations. Table 1 shows that the tested carbonate pore classes may show either no correlation or increase in recovery when they are more homogenous in terms of pore size distribution. The relationship between water flood efficiency and dispersivity seems to be more complex. Dispersivity is a measure of the mixing length of the porous media. One may expect that low dispersive systems have better communication in different directions, and therefore a more piston-like two-phase displacement front, and better sweep and recovery efficiency. The results from these tests confirm such correlation for most pore types. Higher flowing fraction seems to be correlated with higher recovery efficiency by water flooding for thev majority of carbonate pore classes. Exceptions may be made for tertiary chalk with a high recovery and IC-UMi with low recovery efficiency by water flooding. Formation resistivity factor tends to either correlate with recovery for some pore classes or have no correlation.

The cross plots presented in this paper show that oil recovery is related to petrophysics parameters. Oil recovery has a negative correlation to formation resistivity factor (e.g. Figure 3), indicating that carbonate samples with low FF are expected to perform well.

In addition, pore types seem to have petrophysical properties within characteristic ranges (*e.g.* chalk samples can be expected to be low dispersive, while mouldic macro-porosity samples have higher dispersivity (Figure 6)). The fact that the samples of each pore class were selected to have a certain permeability and porosity ranges reinforces the concept of pore types having characteristic values when it comes to other matrix properties. The exception is intercrystalline porosities, showing scattered values for several petrophysics properties (Figures 4 and 6).

For prediction of oil recovery from carbonates, both types of diagrams shown in this paper can be used. According to the recovery versus dispersivity correlation seen in Figure 5 and the pore type behaviour to recovery shown in Figure 1, chalk is a promising material with regards to recovery, both because of the expected low dispersivity and because of the pore class. For prediction of recovery from pore types with less defined grouping and recovery correlations, like intercrystalline material, general trends, as seen in Figures 7 or 8, can be used. For mouldic pore types, by knowing the flowing fraction and applying Figure 7, recovery efficiency by water flooding could be estimated more accurately.

Conclusions

The work described in this paper supports the following conclusions:

- Oil recovery by waterflooding seems to be related to carbonate pore classes.
- Chalk has high recovery, interparticle porosities have intermediate recovery, and mouldic porosities have low recovery. The intercrystalline pore classes show large scatter in recovery.
- Basic matrix properties, like flowing fraction, dispersivity and formation resistivity factor, are related to oil recovery, and can to a certain extend be used in predicting oil production by waterflooding.
- Chalk has high recovery and low dispersivity. The interparticle and mouldic pore classes have intermediate dispersivities, but with different typical recoveries; the interparticle pore class show higher recovery than the mouldic pore class. The intercrystalline pore class showed large scatter in both dispersivity and recovery. Similar conclusions can be drawn from flowing fraction and formation resistivity factors.
- Oil recovery versus. flowing fraction at the water-wet state shows a general trend which is pore type dependent. By knowing the pore type in addition to the flowing fraction, oil recovery can be predicted with higher accuracy. Flowing fraction at S_{or} has a more unique relation to oil recovery, without the pore type dependency. It appears that the presence of residual oil rules out relevant pore type characteristic matrix properties.

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Nomenclatures

FF: Formation Factor, dimensionless
f: Flowing fraction at 100 % water saturated, [frac. of pore volume]
f_{Sor}: Flowing fraction at residual oil saturation, [frac. of pore volume]
K: Absolute Permeability, [mD]
PV: Pore Volume, [cm^3]
OOIP: Original Oil In Place
Rf: Recovery Factor or Recovery efficiency, [fraction of OOIP]
S_{wi}: Initiatal Water Saturation, [fraction of PV]
S_{orw}: Residual Oil Saturation, [fraction of PV]

Subscripts, greek Letters:

α= Dispersivity, [cm]
Φ= Porostity, [fraction of PV]

Pore Class Codes:

IP-UMa: Interparticle Uniform Macro-porosity
IC-UMa: Intercrystalline Uniform Macro-porsity
IC-UMi: Intercrystalline Uniform Macro-porosity
IP-PMe: Interparticle Patchy Meso-porsoity
IC-PMe: Intercrystalline Patchy Meso-porosity
IC-PMi: Intercrystalline Patchy Meso-porosity
M-Ma: Mouldic Macro-porosity
M-Mi: Mouldic Micro-porosity

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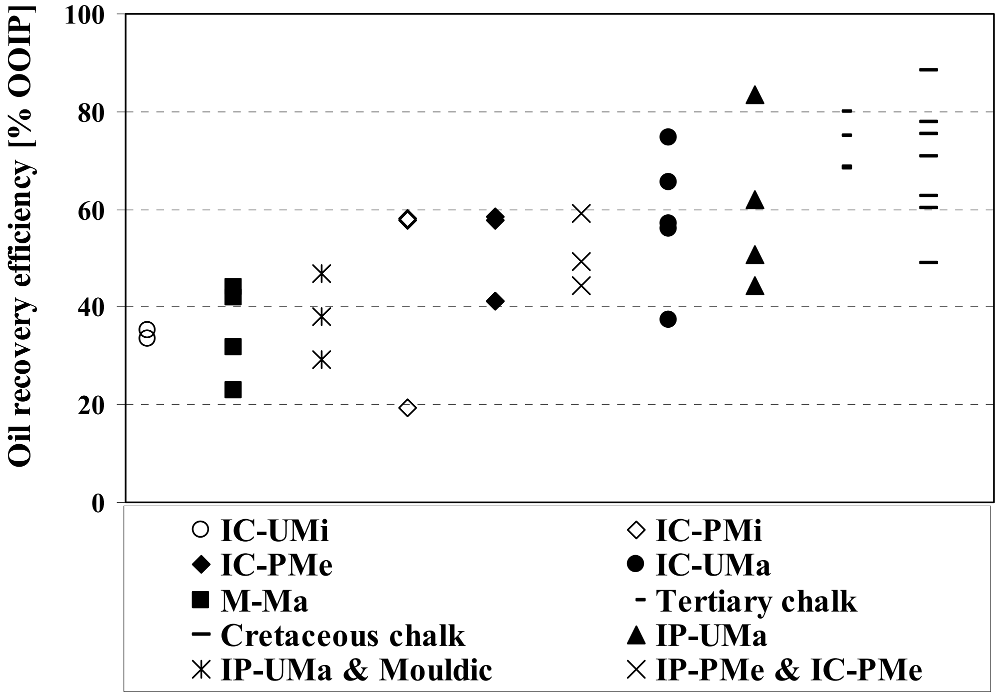

Figure 1: Chart of waterflood efficiency in different carbonate pore classes.

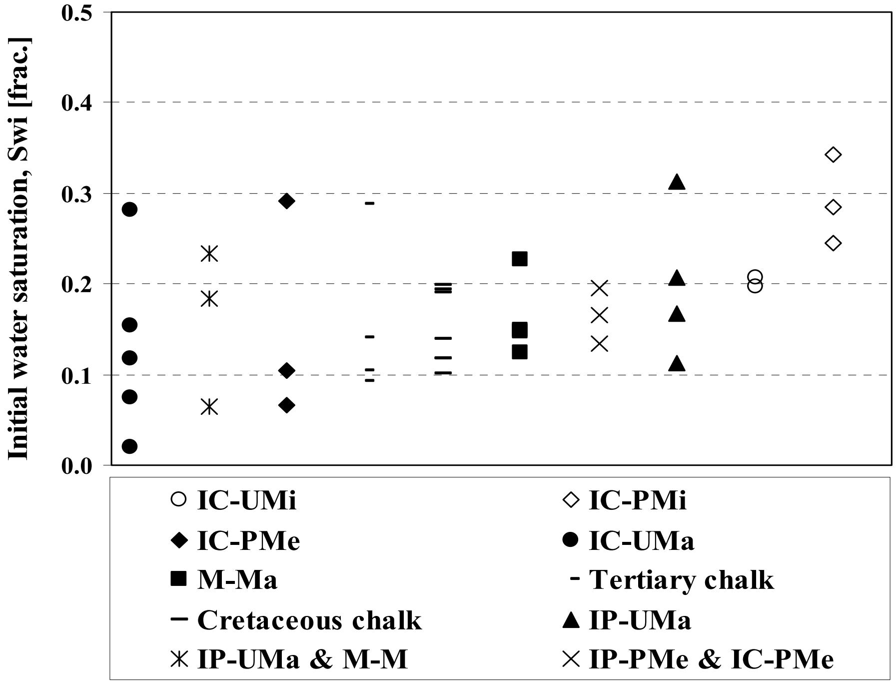

Figure 2: Chart of initial water saturation established prior to waterflooding in different . carbonate pore classes.

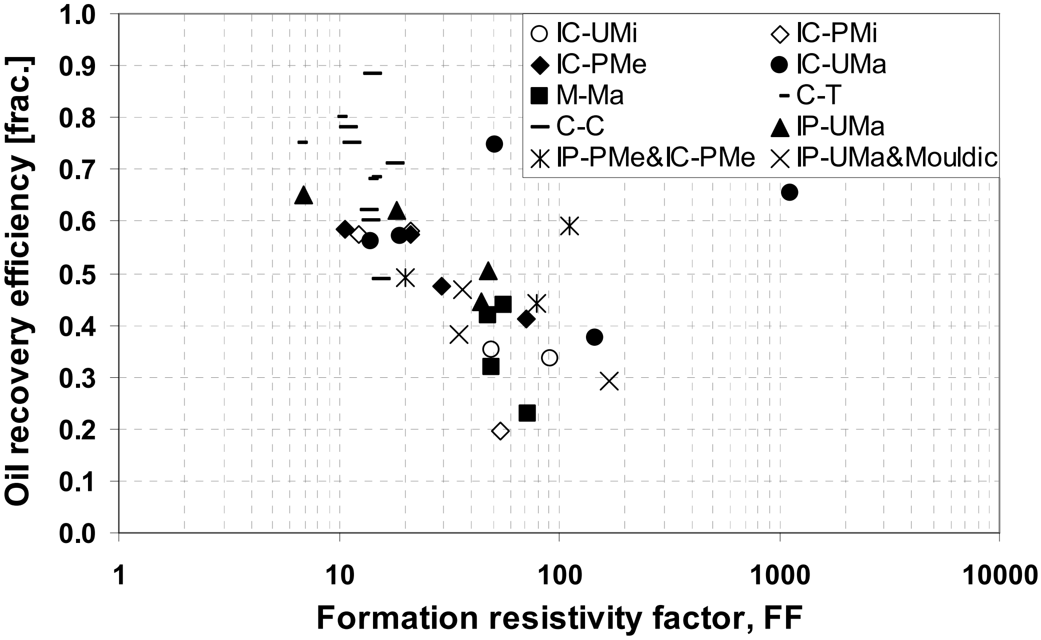

Figure 3: Cross-plot of waterflood efficiency versus formation resistivity factor for the tested samples. The plotted points are marked according to their pore class.

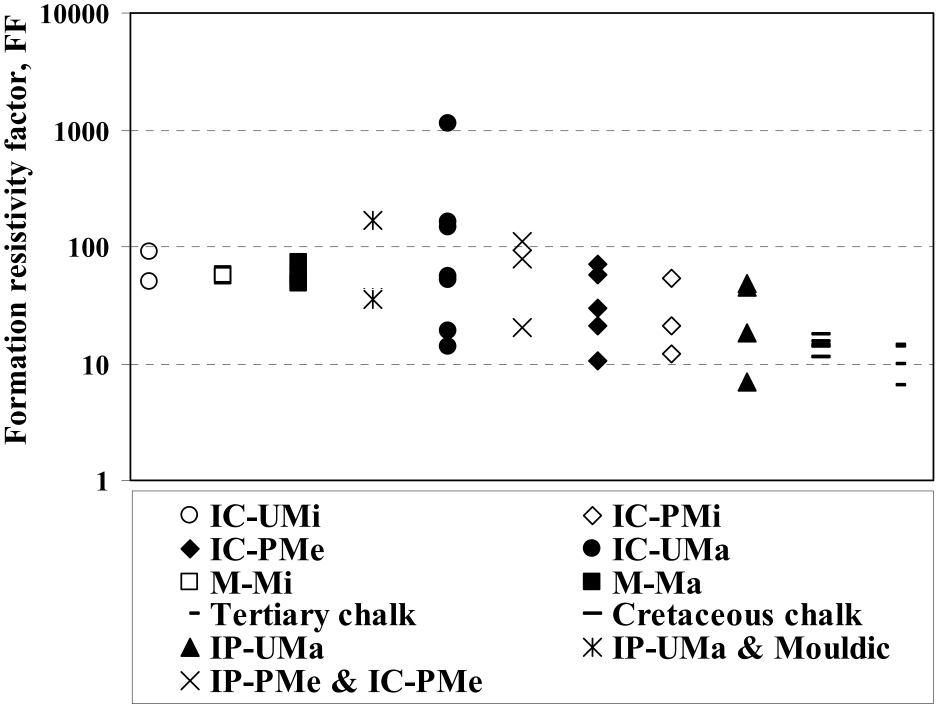

Figure 4: Chart of formation resistivity factor in different carbonate pore types.

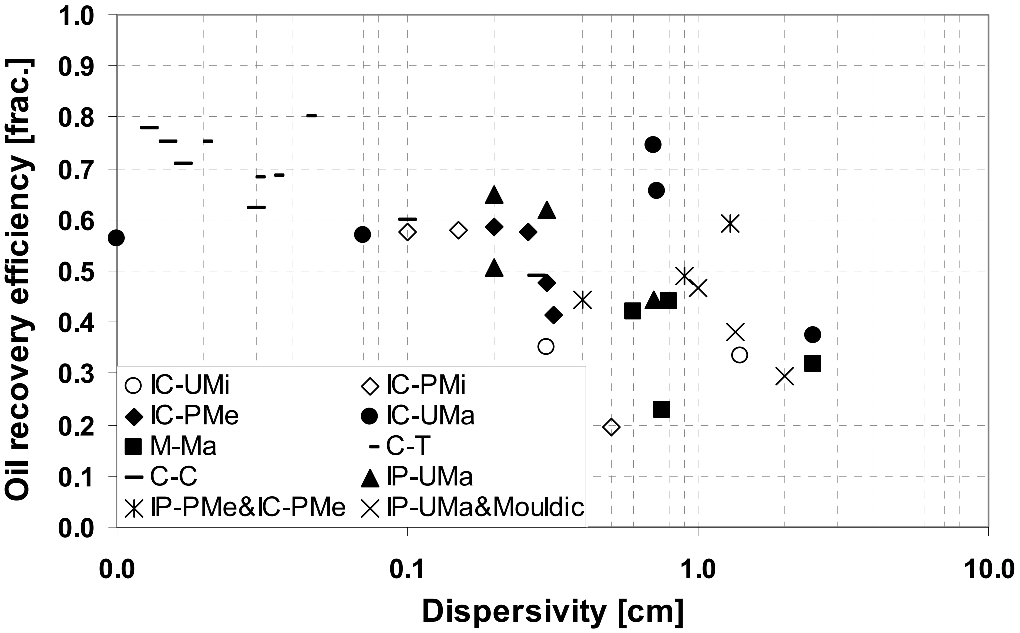

Figure 5: Cross-plot of waterflood efficiency versus dispersivity for the tested samples. The plotted points are marked according to their pore class.

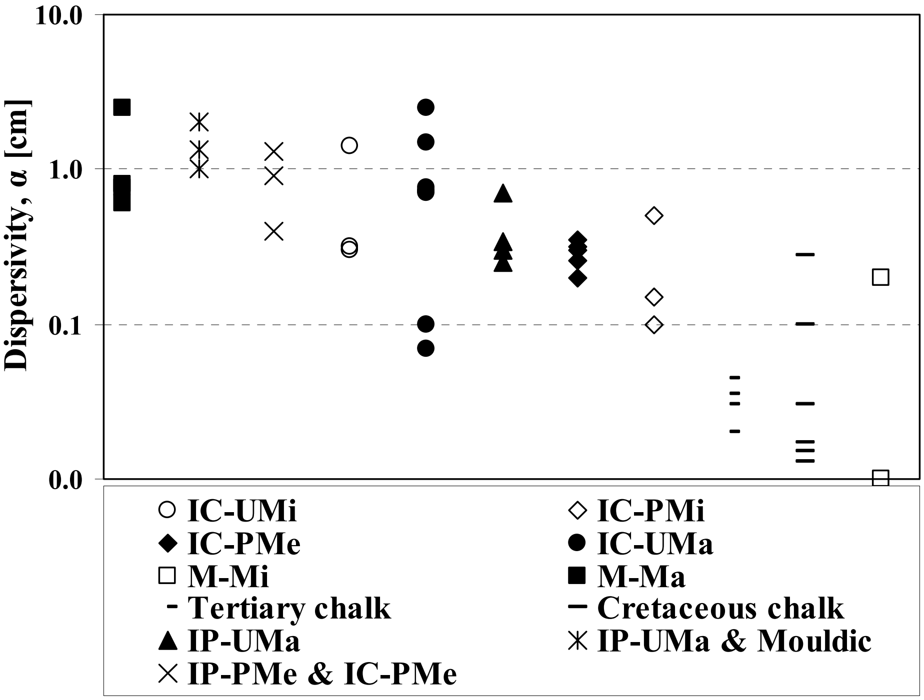

Figure 6: Chart of dispersivity for different carbonate pore classes.

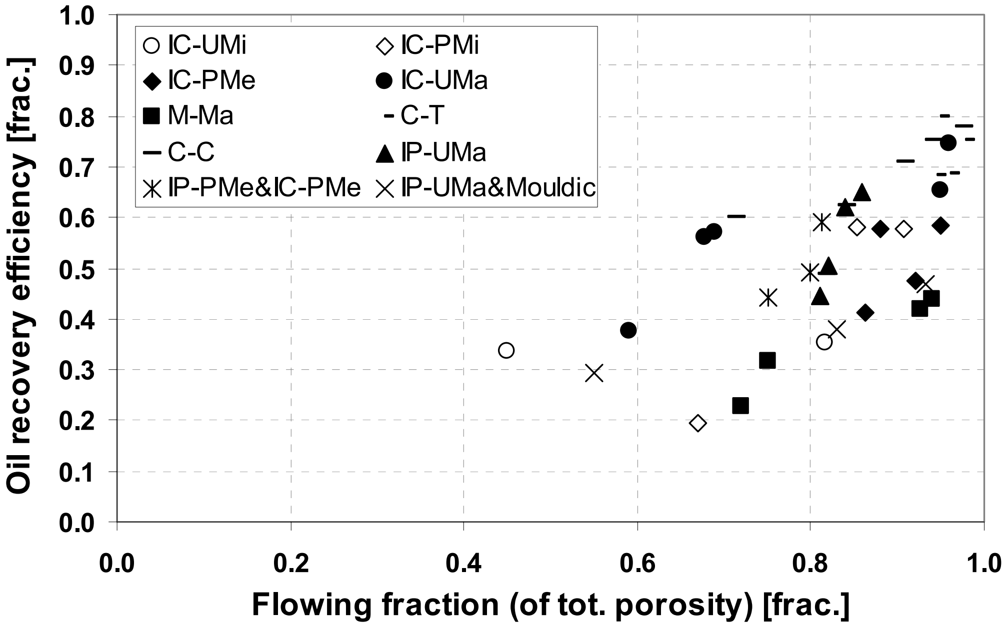

Figure 7: Cross plot of waterflood efficiency versus flowing fraction at 100 % water saturation for the tested samples. The plotted points are marked according to their pore class.

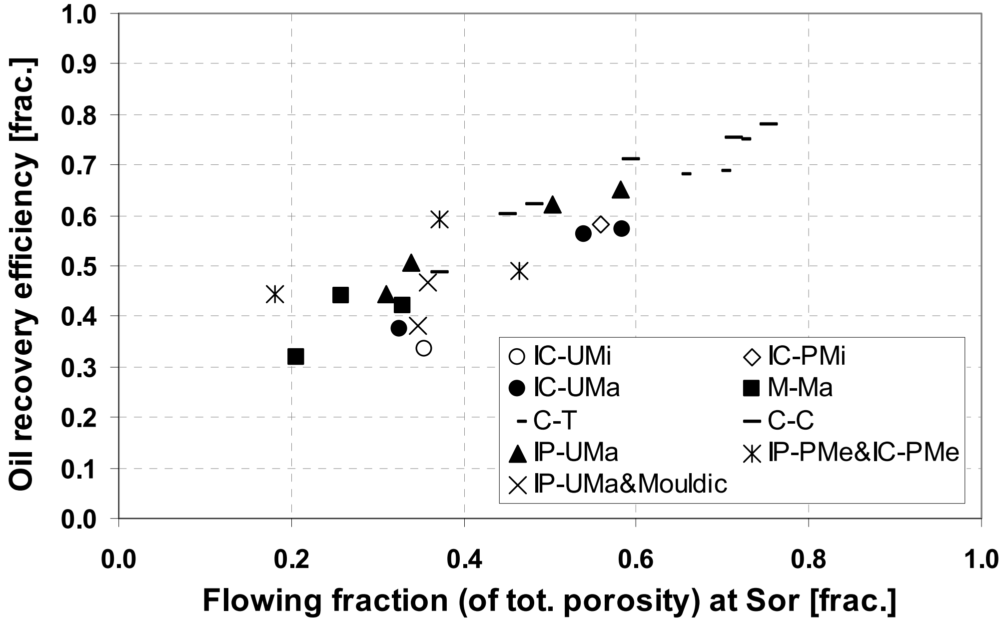

Figure 8: Cross plot of waterflood efficiency versus flowing fraction after for the tested samples. The plotted points are marked according to their pore class.

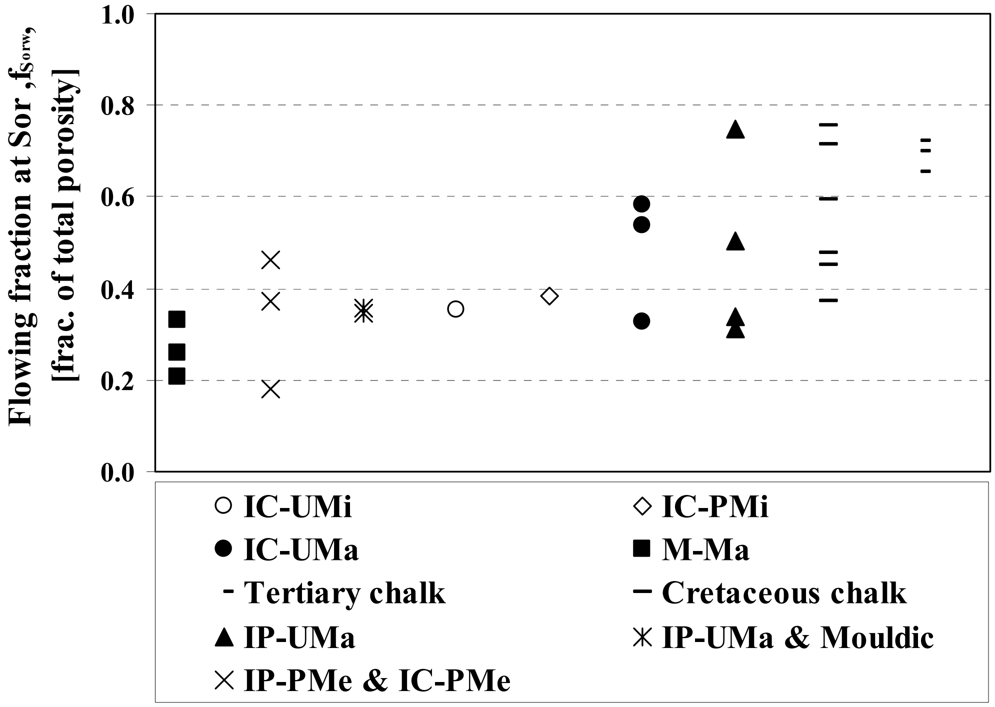

Figure 9: Chart of flowing fraction at residual oil saturation for different carbonate pore classes.

Table 1: Summary of average waterflood efficiency and observed trends between waterflood efficiency and single phase flow properties for different carbonate pore classes.

Pore Class	Pore size distribution index, PSDI	Formation resistivity factor, FF	Dispersivity α	Flowing fraction f	Average waterflood efficiency [% OOIP]
Recovery in IC-UMi	—	—	—	—	34
Recovery in IC-PMi	—	▼	▼	▲	45
Recovery in IC-PMe	▲	▼	▼	▲	48
Recovery in IC-UMa	—	—	—	▲	51
Recovery in mouldic	—	—	—	▲	36
Recovery in tertaiary chalk	▲	▼	—	—	73
Recovery in cretaceous chalk	—	—	▼	▲	69
Recovery in IP-UMa	▲	▼	▼	▲	60
Recovery in IP-PMe & IC-PMe	—	—	▲	▲	51
Recovery in IP-UMa & mouldic	▲	▼	▼	▲	38

▲ **Positive correlation**
▼ **Negative correlation**
— **No correlation**