PAPER IV

IMPACT of PETROPYHYSICAL PROPERTIES on WATER FLOOD EFFICIENCY in CRETACEOUS and TERTIARY CHALK

IV

IMPACT of PETROPYHYSICAL PROPERTIES on WATER FLOOD EFFICIENCY in CRETACEOUS and TERTIARY CHALK

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This paper was prepared for presentation at the International Symposium of the
Society of Core Analysts held in Abu Dhabi, UAE 29 October-2 November, 2008

ABSTRACT

In this paper we report results from an extensive core analysis study to investigate parameters that control oil recovery efficiency by water flooding in chalk reservoirs. Samples included in the study are either of Tertiary or Cretaceous age.

Petrophysical characterization including pore size distribution by different methods and single phase dispersion form a background for understanding pore structure, connectivity and relationship to oil recovery by waterflooding.

Based on measurements on water saturated samples, both types of chalk appear relatively homogeneous with very low values of dispersivity and high flowing fractions. However, there is a tendency for higher flowing fraction- and less dead-end porosity for Tertiary chalk as compared to Cretaceous chalk. This higher flowing fraction correlates with higher recovery. Also, the spread in recovery between different samples is higher, and the porosity is lower for the Cretaceous chalk samples. The Cretaceous chalk samples with restored wettability have lower S_{wi} than the restored Tertiary chalk samples.

In cleaned state, the cores are water-wet. After ageing in crude oil, the wettability of the cores was changed to intermediate wettability, this included both mixed wet and fractional wet states. Analysis of wettability indices indicates that most of the core material displayed a mixed-wet behavior with the oil wet sites in the smaller pores. Surprisingly the large shift in wettability, followed by a strong reduction in spontaneous imbibition, had no significant effect on oil recovery efficiency. It should, however, be noted that there is some degree of spontaneous imbibition in all the core floods that were performed. Nevertheless, the observed behavior may indicate that petrophysical properties, as reflected in dispersion measurements on fully brine saturated samples, are more important in determining oil recovery from the studied chalk samples than changes in wettability, or more precisely changes in spontaneous imbibition.

INTRODUCTION

Chalk has rather small pore throat sizes, usually a few micron in diameter, which may be defined as interparticle or intercrystalline porosity. Chalk micropores are primary in origin and occur between grains of calcareous algae or their component crystal plates (Lønøy, 2006). Subdivision of chalk into Tertiary and Cretaceous chalk is based on a marked decrease in grain size across the Cretaceous-Tertiary boundary (Macleod, 1997), with a corresponding decrease in reservoir quality (Hardman, 1983). Cretaceous chalk generally has higher permeability and less porosity compared to Tertiary chalk in the North Sea (Lønøy, 2006). Good examples of productive zones in the North Sea composed of Tertiary and Cretaceous chalk are found in the Ekofisk and Tor formations of the Ekofisk field (Hermansen *et al*, 1997) and Tor formation at the Valhall field (Tjetland *et al*, 2007).

Chalk has often been described as a rather homogeneous matrix rock material with meso-scale (meter scale) fractures. This dual porosity system has led to a large discussion on fracture-matrix interactions. However, the details of dual porosity seem unnecessary in upscaled fluid flow functions, and the behaviour of field scale flow fronts is rather stable in chalk reservoirs (Hermansen *et al*, 1997).

The assumed water flood efficiency in chalk reservoirs may be due to homogeneous and well-connected matrix, fracture-matrix transport, gravity stable displacement and also compaction drive. As chalk is water soluble material, dissolution of chalk material can occur as the water is not in equilibrium with the composition of injection brine. Compaction has also been a key issue for several oil fields, in particular, the Ekofisk and Valhall fields. Compaction is often related to softening of the rock in contact with injection brine but could also be partly due to dissolution. Some results on Ekofisk Field chalks have demonstrated that the capillary suction cohesion model is not a valid mechanistic description of chalk behavior (Lord et al, 1998). The argument used is that the residual water content of chalk is at least twenty times too low to support capillary water menisci. An alternative weakening mechanism, such as mineral dissolution at grain-to-grain contact points, needs to be considered. The importance of thermodynamic equilibrium has been stressed by Madland, 2005. High quality experimental tests are necessary in order to develop a realistic and accurate model of waterflood compaction response in chalk reservoirs. The waterflooding of chalk reservoirs is influences by compaction as well as fluid flow parameters.

High waterflood recovery for chalk has been observed in recent experimental studies (Webb *et al*, 2005, Pourmohammadi *et al*, 2008). Skauge *et al*, (2006) reported that oil recovery for carbonates is not dependent on the amount of spontaneous imbibition. Although spontaneous imbibition have attracted a lot of attention, it is our opinion over-emphasised, as even a very low degree of spontaneous imbibition seems to be sufficient to ensure high oil recovery. Masalmeh *et al* (2003, 2006) showed that even without any spontaneous water imbibition core data of carbonate samples still showed high recovery and very low residual oil. The oil recovery on larger scale shows this even clearer, as viscous and gravity forces may dominate performance at the field scale. The exception is cases were there is no spontaneous water imbibition at all, where this fact prevents contact to part of the formation (Masalmeh *et al*, 2003). However, for field cases, the recovery is controlled by geological heterogeneity which becomes much more significant for the cases of no spontaneous imbibition (the case mentioned in Masalmeh et. al 2003), as capillary forces forms a barrier for water to cross flow from high to low permeability layers and results in poor sweep efficiency, but not necessarily poor displacement efficiency.

Hamon (2004) shows that there is a stronger spontaneous water imbibition closer to the water-oil contact both for the Eldfisk and Ekofisk reservoirs. It is possible that there also is a trend for less water-wet rock with increasing height above the water-oil-contact, but this would depend on the change in spontaneous water imbibition being proportional to a change in wettability.

Earlier studies by Skauge *et al*, (2006) showed a link between single phase flow properties characterized by dispersion experiments and water flood efficiency for carbonates in general. Recently, Pourmohammadi *et al*, (2007) reported variation in single phase fluid flow properties of different carbonate pore systems from laboratory experiments. The results characterize chalky pore systems (natural chalk) as the most homogenous carbonate pore class, with the lowest dead-end porosity. This work is a further characterization of chalk materials including both Tertiary and Cretaceous chalk. The objective was to investigate petrophysical parameters that may control recovery by water flooding.

EXPERIMENTAL

The data presented in this paper is obtained from an extended experimental SCAL and petrophysics program covering several carbonate pore classes.

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 (pore size distribution by NMR, and in establishing S_{wi}). Degassed and filtered crude oil was used during ageing at elevated temperature, and a slug of toluene was used as buffer fluid between decane and crude oil when one was displacing the other.

The aging time was one month at an elevated temperature of 90ºC. The ageing procedure involved continuous flooding of crude oil at alternating directions in order to provide the entire pore volume available to oil with the surface active agents, and thereby secure a homogenous wettability alteration.

Prior to experiments, all samples were cleaned by warm miscible solvent flooding, and saturated with synthetic sea water.

Dispersion tests were performed by miscible displacing SSW from the pores by a brine solution with slightly higher NaCl-content. The characteristic dispersion profile is measured directly by continuous on-line conductivity measurement of the effluent. Dispersion tests were performed in both cleaned (at S_w=1 and S_{or}) and restored wettability state (S_{or}).

Wettability tests on cleaned samples followed the Amott-Harvey procedure, with spontaneous imbibition and flooding displacement from S_{wi} to S_{or}, and back again. The wetttability measurements after cleaning show an average wetttability index of 0.9 ± 0.04 for all Cretaceous Chalk and two Tertiary Chalk. The exceptions are two Tertiary chalk showed AH of 0.65 and 0.3. The water flooding profiles in the cleaned state show water wet response, as where no significant oil produced after water breakthrough. Wettability tests on restored samples additionally included centrifuge measurements of both positive and negative capillary pressure curves, and hence both the Amott-Harvey and the USBM indices could be estimated.

Water flooding was performed with constant injection rate, and continuous acquisition of differential pressure and oil production. Two bump rates were applied at the end, with maximum differential pressure of 30 bar. The water flooding in each step was continued until no oil production was observed. The whole process (All three steps from the initial rate to the final bump rate) some times required more than 10 volumes of water to be injected. Water flooding was performed at both cleaned and restored wettability state.

RESULTS and DISCUSSION

The present study investigates the impact of wettability and petrophysical properties on oil recovery by waterflooding, including also data on spontaneous imbibition, from reservoir core material classified as either Cretaceous or Tertiary Chalk. The dataset includes samples from the Tor and Ekofisk Fm of the Ekofisk reservoirs, but samples from another Cretaceous chalk reservoir have also been included.

Earlier petrophysics studies, (Pourmohammadi *et al*, 2007), have shown that both Tertiary and Cretaceous chalk are characterized by well connected pore structure, high flowing fraction and less dead-end porosity, less degree of convective mixing, considerable lower tortuosity, low pore size heterogeneity, and more homogeneous compared to other carbonate pore classes.

The Tertiary and Cretaceous chalk have similar primary drainage properties, described by the Leverett J-function relationship in Figure 1. These results are in agreement with earlier studies by Torsæter (1984). The pore throat size distribution is typical for chalk with a very narrow radius distribution in the range around 1 micrometer. In addition to Mercury intrusion, NMR derived pore size distribution has also been estimated. Figure 2 shows pore size distribution by NMR measurements for Cretaceous and Tertiary chalk samples based on a restricted diffusion method developed by Sørland *et al,* (2006). Tertiary chalk and the two types of Cretaceous chalk all confirm a narrow pore size distribution as compared to other carbonate and sandstone material, (Pourmohammadi *et al*, 2007).

Wettability measurements performed on cleaned cores, show a strongly water wet state for all Cretaceous samples, as well as for two of the four Tertiary chalk samples. Wettability indices are given in the experimental section. It should be noted that the same cleaning procedures and conditions were applied for all samples. Figure 3; illustrate a typical change in spontaneous imbibition between cleaned and aged core samples. In all cases the aged cores showed a significant reduction in spontaneous imbibition.

The effect of rock properties on spontaneous imbibition in the chalk samples from the Ekofisk area has been investigated by Torsaeter (1984). Water injection after spontaneous imbibition in Cretaceous chalk (Tor Fm) samples gave no additional oil production (Torsæter, 1984). Further, the residual oil saturation after water imbibition was nearly constant for 24 core samples. In contrast, oil recovery by spontaneous imbibition from Tertiary chalk samples (Ekofisk Fm) was highly unpredictable, and subsequent water injection generally gave additional oil production. It was concluded that difference in imbibition and recovery behaviour of Cretaceous and Tertiary chalk samples is mainly due to wettability differences, with the Tor formation as the more water wet core material. Since the pore structure in the Tor and Ekofisk Fm are very similar, this difference was ascribed to subtle differences in surface chemistry between the formations. The initial and endpoint saturations was correlated with porosity for cores from the Tor formation, while for the Ekofisk formation the saturation and imbibition did not correlate with porosity or any other rock property. Our results are in agreement with the trend observed by Torsæter.

Oil recovery from fractured chalk reservoirs in the North Sea has historically been assumed to be dominated by spontaneous imbibition of water from the fractures into matrix blocks during waterflooding. However, spontaneous imbibition depends on wettability and it is not the only driving force of oil recovery in fractured reservoirs. In the case of intermediate wettability, viscous and gravity forces are also considerable in oil recovery by water flooding. We have investigated the importance of only viscous and capillary forces on recovery for chalk samples at the laboratory scale by altering wettability from the water wet to the intermediate state.

Experiments showing changes in spontaneous imbibition have, in the literature, been interpreted as either due to changes in wettability or changes in oil recovery. We claim that spontaneous imbibition is at best only a part of the wettability property of the core, and that oil recovery by spontaneous imbibition can be misleading in estimating oil recovery by waterflooding. The further discussion will introduce examples to these arguments.

After aging all Cretaceous cores showed an intermediate wettability characterised as a mixed wet small type from USBM and Amott-Harvey wettability indices (see Fig. 4). The wettability class identification follows from earlier studies (Dixit *et al*, 1998, Skauge *et al*, 2004 and 2007). Tertiary chalk is both grouped as mixed wet small and mixed wet large. The more complex wettability variation found for Tertiary chalk agrees with petrophysical properties, and the lack of correlation found for Ekofisk samples in the paper by Torsaeter (1984).

As can be seen from Figure 5, all the chalk cores display high waterflood oil recovery independent of wettability. The cleaned cores show strong spontaneous imbibition, but in general, the spontaneous imbibition is not correlated to high waterflood efficiency. There is, however, a general trend of higher recovery for the samples of low spontaneous imbibition. This is as expected for more Amott defined water-wet samples (that show high spontaneous imbibition) also tend to trap more oil, Skauge et al (2004).

Field pilots on the Tor and Ekofisk formation measuring residual oil saturation confirm that the degree of spontaneous imbibition is of little importance for oil recovery. Data of residual oil saturation for Ekofisk formation (less spontaneous imbibition) is about the same as for Tor formation (more spontaneous imbibition) (Hermansen *et al*, 1997). The field results are consistent with our laboratory results, showing that total waterflood response is independent of the degree of spontaneous imbibition. This conclusion was also drawn from our earlier experimental studies on carbonates, where oil recovery by waterflooding seems to be independent of the amount of spontaneous imbibition as long as there is some degree of spontaneous imbibition (Skauge *et al*, 2006). If the rock does not imbibe water at all the conclusion is no longer valid.

Experimental results on Valhall reservoir cores (Valhall is mainly Tor formation, lower Cretaceous) also show high waterflood efficiency independent of degree of spontaneous imbibition. The spontaneous imbibition showed some variation with the chemical composition of the brine, but did not affect the total oil recovery by waterflooding (Webb *et al*, 2005).

Total waterflood recovery versus recovery by spontaneous imbibition for cleaned chalk cores can be seen in Figure 5. The results show that for Tertiary chalk, the total waterflood recovery is not correlated to spontaneous imbibition. Cretaceous chalk 1 (Tor formation), however, is dominated by strong spontaneous imbibition, while for the Cretaceous chalk 2 (Oseberg formation) the total waterflood recovery increases with increasing spontaneous imbibition.

Single-phase dispersion has been used to describe the connectivity of carbonate material (Skauge *et al*, 2005). Simulation of single-phase tracer production profiles quantifies dispersivity, flowing fraction, dead-end pore fraction and inaccessible pore volumes. The dispersivity is a measure of the sample heterogeneity, with low dispersivity being characteristic of relatively homogeneous porous media. We have applied a similar analysis on the chalk cores and have found lower waterflood recovery for cores with higher dispersivity (see Fig. 6). Based on measurements on fully water saturated samples, both types of chalk appear relatively homogeneous with very low values of dispersivity and high flowing fractions. Higher dispersivity indicates a larger mixing zone and less well connected porous medium. However, there is a tendency for higher flowing fraction- and less dead-end porosity for Tertiary chalk as compared to Cretaceous chalk. This higher flowing fraction correlates with higher recovery. Also, the spread in recovery between different samples is higher, and the porosity is lower for the Cretaceous chalk samples. The Cretaceous chalk samples with restored wettability show lower S_{wi} than the restored Tertiary chalk samples.

CONCLUSIONS

All chalk material tested (representing both Tertiary and Cretaceous chalk) have similar primary drainage properties, and the pore size distribution is narrow compared to other carbonates and sandstones

Oil recovery by waterflooding is high for chalk material independent of the core wettability. Cores with higher dispersivity have lower oil recovery

In general, spontaneous imbibition is not correlated to waterflood efficiency for chalk material. Although, the chalk material tested (representing both Tertiary and Cretaceous chalk) have similar petrophysical properties, the waterflood characteristics differs between the pore classes and type of formation.

Tertiary chalk (Ekofisk formation) show that total waterflood recovery is not correlated to spontaneous imbibition.

Cretaceous chalk type 1 (Tor formation) is dominated by strong spontaneous imbibition.

Cretaceous chalk type 2 (Oseberg formation) show an increase in waterflood recovery with increasing spontaneous imbibition

ACKNOWLEDGMENT

The authors acknowledge StatoilHydro for support to PhD candidate Shahram Pourmohammadi and to the carbonate research program at CIPR.

NOMENCLATURES

C1: Cretaceous Type 1
C2: Cretaceous Type 2
FW: Fractional Wet
J: Leverett J-function, [Dimensionless]
MWL: Mixed- Wet Large

MWS: Mixed-Wet Small
NMR: Nuclear Magnetic Resonance
OOIP: Original Oil in Place
S: Surface, [m^3]
SSW: Synthetic Sea Water
S_{Hg}: Mercury Saturation
Swi: Initial water Saturation
Sor: Residual oil saturation
T: Tertiary chalk
V: Volume [m^3]

REFERENCES

Dixit A.B., Buckley J.S., McDougall S.R. and Sorbie K.S. (1998), “Core Wettability: Should IAH equal to USBM?”, paper presented at the International Symposium of the SCA, the Hague, the Netherlands, September.

Hamon, G. (2004), “Revisiting Ekofisk andf Eldfisk wettability,” SPE 90014

Hardman, R. F. P. (1983), “Chalk hydrocarbon reservoirs of the North Sea – An introduction”, Proceedings of the JAPEC Chalk Seminar, 15 December 1983, pp. D1-D33

Hermansen , H., Thomas, L.K., Sylte, J.E., and Aaseboe, B.T. (1997), “Twenty Five Years of Ekofisk Reservoir Management,” SPE 38927-MS, presented at the SPE Annual Technical Conference and Exhibition, San Antonio, Texas, 5-8 Oct. 1997.

Lord, C. J., Johlman, C. L. and Rhett D. W.(1988) ” Is Capillary Suction a Viable Cohesive Mechanism in Chalk?”, SPE/lSRM 47310,Presented at the SPE/lSRM Eurock 98 Held in Trondheim, Norway 8-10 July

Lønøy, A.,”Making Sense of Carbonate Pore Systems”, AAPG Bulletin, (2006), v. 90, no. 9, pp. 1381-1405.

Macleod, N., (1997)”The Cretaceous-Tertiary Biotic Transition”, Journal of the geological Society (London), v. 154, pp. 265-292.

Madland, M, V. (2005), “Water weakening of chalk: A mechanistic study,” PhD thesis Univ. of Stavanger, June 2005

Masalmeh, S. K., Jing, X. D., van Vark, W., Christiansen, S., van der Weerd, H., van Dorp, J. (2003)"Impact of SCAL on carbonate reservoirs: how capillary forces can affect field performance predictions," SCA2003-36, paper presented at the International Symposium of the Society of Core Analysts, Pau, France, September, 2003

Masalmeh S.K., and Jing X.D., (2006), “Capillary Pressure Characterisitcs of Carbonate Reservoirs: Relationship Between Drainage and Imbibition Curves, SCA 2006-16, reviewed proceedings at the International Symposium of the Society of Core Analysts, Trondheim, Norway, 12-16 September 2006

Pourmohammadi, S., Hetland, S., Spildo, K., and Skauge, A. (2007), “Fluid Flow Properties of Different Carbonate Pore Classes,” SPE 111433, presented in Abu Dhabi, the United Arab Emirates, 28-31 October 2007.

Pourmohammadi, S., Hetland, S., Spildo, K., and Skauge, A. (2008), “Does the Pore Class Conceptfor Carbonates Make Sense for Multi-Phase Flow? , Submitted to proceeding in the 2008 International Symposium of the Society of Core Analysts (SCA), Abu Dhabi, UAE, 29 October – 2 November.

Skauge,A., Høiland,L., Vik,B., Spildo,K., and Ottesen,B. (2004) ”Experimental evidence of different intermediate wetting states”, reviewed proceeding from the 2004 International Symposium of the Society of Core Analysts (SCA), Abu Dhabi, Sept.

Skauge, A., Spildo, K., Lønøy, A., Njøten, G., and Ottesen, B. (2005), “Waterflood Efficiency for Different Pore Classes in Carbonate Reservoirs,” presented at 13th European Symposium on Improved Oil Recovery, Budapest, Hungary, 25-27 April

Skauge, A., Sørvik, A., Vik, B., and Spildo, K. (2006), “Effect of wettability on oil recovery from carbonate material representing different pore classes”, reviewed proceedings at the International Symposium of the Society of Core Analysts, Trondheim, Norway, 12-16 September 2006

Skauge, A., Spildo, K., Høiland, L., and Vik B. (2007) “Theoretical and experimental evidence of different wettability classes,” Journal of Petroleum Science and Engineering 57, 321–333

Sorland G.H., Djurhuus K., Lien, J.R. and Skauge, A., (2006), “Absolute Pore Size istributions from NMR”, reviewed Proceedings at the International Symposium of the Society of Core Analysts, Trondheim, Norway, 12-16 September

Tjetland, G., Kristiansen, T.G., and Buer, K. (2007), ”Reservoir Management Aspects of Early Waterflood Response after 25 Years of Depletion in the Valhall field,” IPTC 11276, held im Dubai, U.A.E. 4-6 Dec.

Torsæter, O. (1984), ”An experimental study of water imbibition in chalk from the Ekofisk Field” paper SPE 12688, presented at the 4th SPE/DOE IOR symposium, Tulsa, April 15-18, 1984.

Webb, K.J., Black, C.J.J., Tjetland, G. (2005), “A Laboratory Study Investigating Methods for Improving Oil Recovery in Carbonates,” IPTC 10506, held in Doha, Qatar, 21-23 Nov. 2005

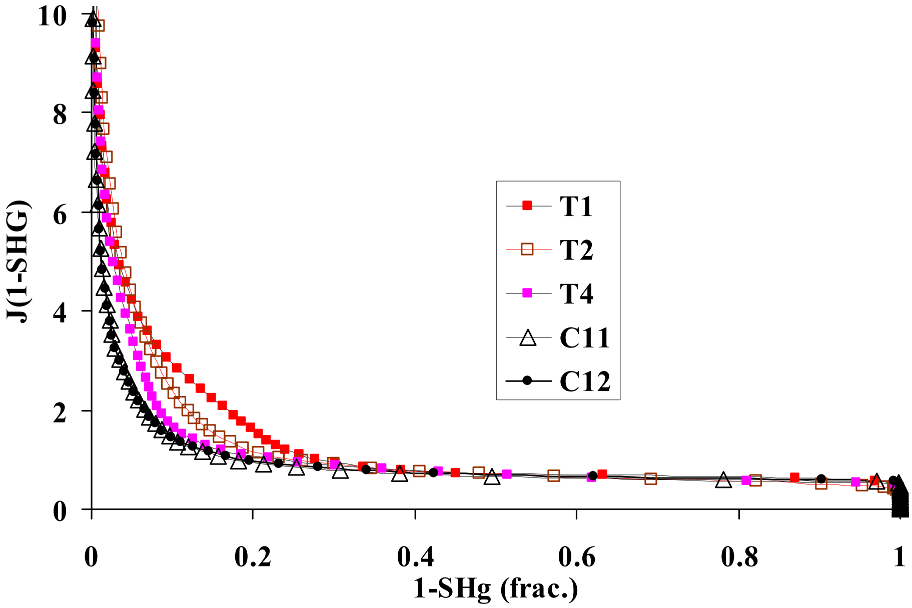

Figure 1. Leverett J-function for Cretaceous and Tertiary chalk cores

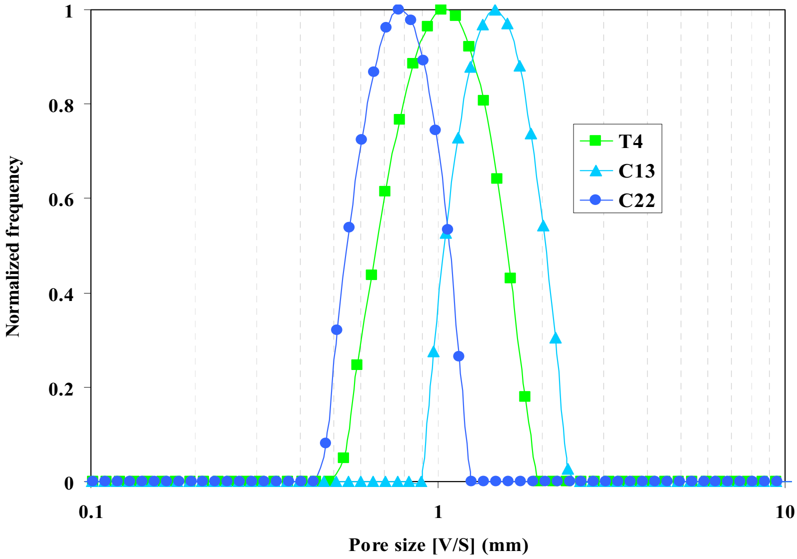

Figure 2. Pore size distribution derived from NMR measurements

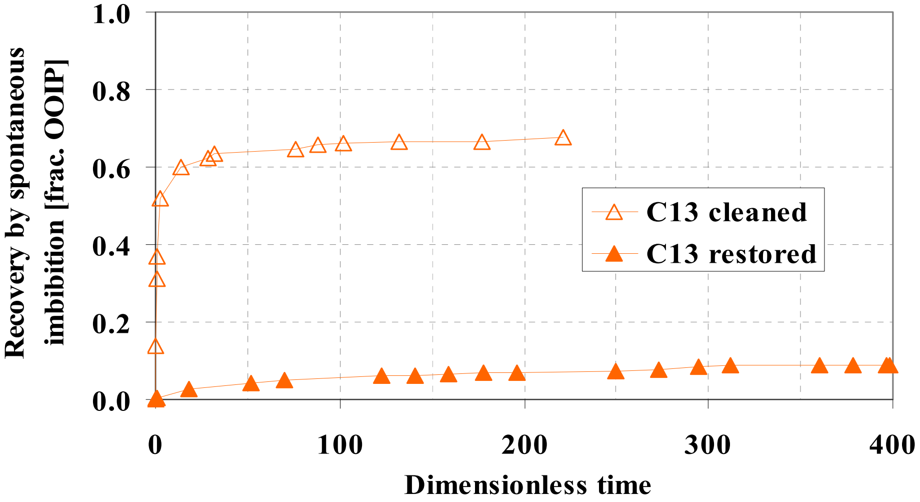

Figure 3. Example of change in spontaneous imbibition for a cleaned and aged Cretaceous Chalk core.

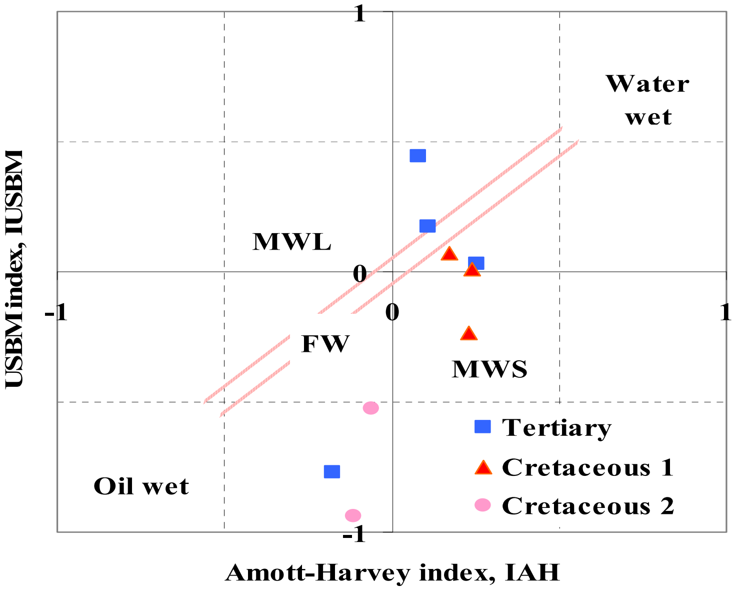

Figure 4. Wettability indices for chalk cores. Points below the two non-continues lines indicate mixed wet small wettability.

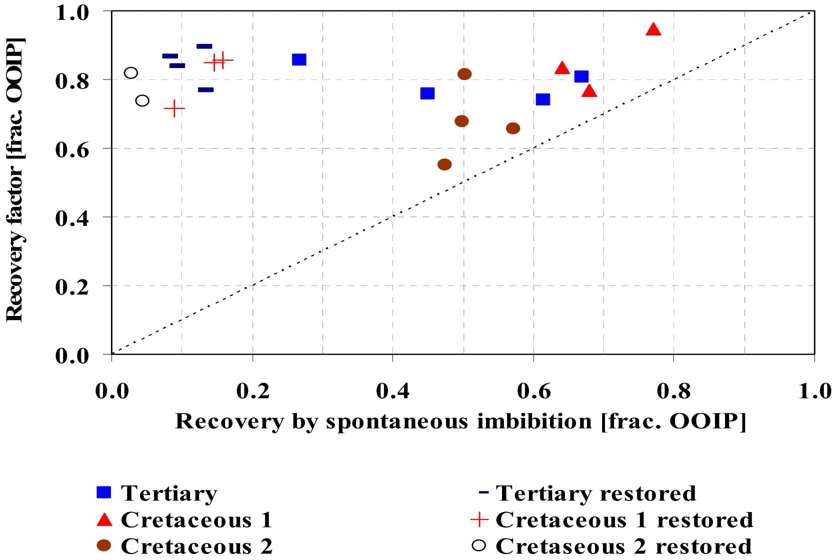

Figure 5. Total waterflood oil recovery as a function of spontaneous imbibition, for cleaned and aged cores (both Tertiary and Cretaceous chalk cores)

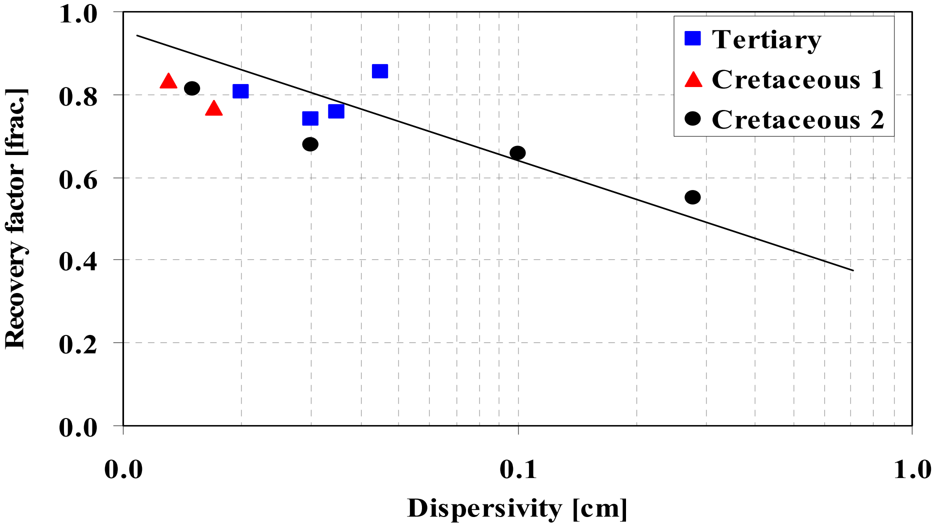

Figure 6. Oil recovery versus core dispersivity.