ANOTHER LOOK AT EKOFISK WETTABILITY

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ABSTRACT:

The Ekofisk field, located in the North Sea, is currently waterflooded to increase the oil recovery of this naturally fractured, low matrix permeability, chalk reservoir. The wettability of this reservoir has long been a concern due to the extensive fracture network and was widely studied. However, the large and unexplained scatter in wettability index and the discrepancy between laboratory and water injection results has led to questions about the extent to which the laboratory data are representative of reality. Recently, a review of 250 wettability tests has been performed. The effect of a large number of parameters has been investigated including reservoir data and core handling and laboratory procedures.

Two approaches have been used to decipher the effect of these parameters on the wettability index for this large data set: rule finding and regression techniques.

The main results of this review are:

- A strong relationship in the Ekofisk field between the water wetness and the elevation above the free water level, whatever the laboratory experimental conditions,
- A clear tendency of increasing water-wet characteristics with depth,
- A significant noise regarding this main trend due to experimental conditions.

In the second part of this paper, the method used to generate the matrix water-oil relative permeability curves using pore network modelling is described. This approach allows incorporating the variations of both the rock characteristics and of the depth dependent wettability and complements the experimental core floods when no data is available for a given combination of lithology and wettability.

INTRODUCTION:

The large contrast between the low permeability of the chalk and the high productivity of the early Ekofisk wells was identified very early and focused the attention on the extensive fracture network observed in cores [1]. Therefore, in the early 80s, spontaneous imbibition was deemed to be the main recovery process should the water be injected in this fractured reservoir. The laboratory work on the wettability of the Ekofisk field started in the late 70's and was carried out on samples from wells 2X, 4AX and mainly from wells A8 and B16 [2]. Samples were extracted with xylene and methanol, dried, evacuated and saturated with formation water, then driven to irreducible water saturation by centrifugation. Amott-Harvey wettability tests were performed on more than one hundred samples. It was concluded that: 1) the Tor formation is strongly water-wet and the amount of spontaneous imbibition ranges from 40% to 60% and correlates well with porosity, 2) a large scatter in wettability was observed for the Ekofisk formation and the amount of spontaneous imbibition did not correlate with any rock property. In the Ekofisk formation, the majority of samples indicated imbibition in the range of 15% to 25% [3].

As the pore structure of both formations was very similar, the difference in wettability was ascribed to subtle differences in surface chemistry. However, as the spatial variation of these differences remained unknown, the wettability variations and then the imbibition behaviour were unpredictable.

Further wettability tests were carried out on samples from well C-8 and the sensitivity of the amount of spontaneous imbibition to different parameters was investigated [1] . Experiments were carried out with refined oil or reservoir oil, at room or reservoir temperature. Samples were either preserved or extracted and restored. The effect of temperature and of the type of oil was deemed significant but the influence of the preparation of the samples was not found very important [1]. Wettability to water of the Tor formation was deemed to be confirmed by the excellent results of the waterflood pilot (1981-1984). This waterflood pilot was simulated with a dual porosity model assuming that the water saturation at zero water/oil capillary pressure was 0.625, e.g. a strong water imbibition [1]. Full scale water injection was then implemented in the Tor formation and started in 1987 [4]

Based on the deceptive results of the spontaneous imbibition tests, the Ekofisk formation was first given a low waterflood priority. However, the results of the Lower Ekofisk waterflood pilot (1986-1988) were rather good [3]. The comparison of logs of the original B-16 well and a side tracked location indicated an average water saturation increase from 10% to 60% in the waterflooded zone. This was substantially higher than laboratory measurements. The long period of water-free production of two producers also suggested that the water retention in the reservoir was much larger than estimated from the laboratory imbibition [3]. The results of this pilot:

- Increased the suspicion against laboratory results [3, 5]. The causes of the discrepancies were not clear [3] or it was suspected that the more favourable (but scarce) imbibition tests carried out at elevated temperature would be more representative of the reservoir conditions than the more conservative (but widely available) imbibition tests performed at room temperature [5].
- Or suggested that significant volumes of oil could be mobilized in the Ekofisk Fm with small pressure differentials [3]. Further phenomenological studies were devoted to the impact of viscous forces and block-to-block continuity in scarcely fractured reservoirs such as Ekofisk [6, 7]. Both numerical and experimental studies concluded that the effect of viscous forces increases the oil recovery in intermediate-wet, fractured rocks if matrix-to-matrix continuity is assumed between the matrix blocks.

An injectivity test in the Upper Ekofisk formation was then performed in 1990. A sidetrack of the injection well 160 feet away showed lower residual oil saturations than anticipated from laboratory studies, but the results were less favourable compared to the Lower Ekofisk and Tor formations [8].

The expansion of waterflooding to full field has been successful [8]. The current ultimate oil recovery estimate is 38% of OIP and several oil recovery methods have been studied [10]. In addition, a refined analysis of the water injection performance and opportunities to optimize the waterflood are ongoing. Despite the suspicion against the results of the wettability tests on Ekofisk, it was decided to review the existing results, in order to refine the estimate of the microscopic waterflood behaviour.

REVIEW OF WETTABILITY DATA:

Data Gathering:

A first look at the data confirmed a large scatter in wettability results. The main objective of the study is then to conclude whether this large variation of wettability does exist within the Ekofisk field or whether the large scatter is mainly due to experimental artefacts.

Although wettability tests are rather standard laboratory tests in the oil industry, this study faced significant difficulties when the data were compiled:

- Both the experimental techniques and the type of reported data were very different over the 20 years period of data acquisition. For instance, in the early 90s, the core preparation procedures for spontaneous imbibition tests were modified to force the results to be more in agreement with in-situ observations [8].
- Incomplete reporting has been the rule rather than the exception for both the details of the laboratory procedures and the final results, particularly for the early work.
- Very few ancillary data were acquired in addition to wettability tests. For instance, mercury injection capillary pressure curves, or any other type of characterisation of the pore network were very rarely available on plug trimmings.

The amount of spontaneous imbibition to water has been selected as the wettability indicator, in order to study the largest data set. Other wettability indexes: to water, to oil, or both are not presented in this paper. These wettability indexes were available on a very limited number of samples, related to a specific well, zone of the reservoir, or laboratory procedure.

In order to decipher the variability of the Ekofisk wettability, each wettability test has been documented by 25 parameters including:

- Reservoir data: Formation, well, coring date (from 1974 to 1997), true vertical depth, porosity, sample permeability
- Core handling and laboratory procedures: coring fluid (water-base mud or oil-base mud), type of wettability preservation (native-state, cleaned, cleaned and restored), elapsed time between coring and laboratory work, laboratory name, cleaning method (Soxhlet extraction, cold flooding, hot flooding), cleaning solvents, initial water saturation, method used to achieve Swi, type and characteristics of oil used during the wettability tests (refined, dead reservoir, viscosity), temperature during the ageing period and during wettability tests.

More than 250 wettability tests have been reviewed. These tests originate from ten Ekofisk wells: 2/4-2X; 4AX, A6, A8, B4, B12, B16, C8, X9, X47. Core samples were taken in both Ekofisk and Tor Formations.

Data Analysis:
A large number of data analysis techniques are available, some of which are widely used in geosciences, such as correlation analysis, neural networks, and clustering. Correlation techniques are widely used when trying to explain and predict a variable from other variables. But the review of SCAL results, such as the Ekofisk wettability data set, raises some specific issues:

- A lot of variables are sparsely documented. A lot of useful data have not been systematically measured or reported, such as the initial water saturation. Wettability to oil is available on a very limited amount of samples, as the attention was focused on the oil recovery by water imbibition.
- Some variables are qualitative rather than quantitative (for example, oil viscosity may be described as “viscous” in some reports, without any accurate value).
- Several variables are non-numeric: they describe some important steps of the laboratory procedure.
- Some variables may be rather noisy. There is no clear definition of the residual oil saturation, for instance. Reported Sorw values may refer to widely different and often unknown levels of oil relative permeability or capillary pressure, depending on the laboratory and on the date. These values may originate from different interpretation processes (average value, analytical interpretation, numerical simulation for waterfloods or centrifuge tests).
- The data set may be small and the number of variables may be significant compared to the number of data points.

Even if we did not face the last issue for the Ekofisk wettability, it is clear that, such a data set is not fully appropriate for standard multivariate statistics. Two different approaches have been used separately to show the main controls of the Ekofisk wettability: standard correlation techniques and dedicated data mining software. Use of regression techniques was guided by expertise on the controls of wettability [11-14]. Data mining techniques developed for understanding and controlling complex interactions in production processes were used to quickly generate rules from the whole data set between wettability and other variables. The method used is highly resilient to missing data and noise. This bottom-up learning approach does not rely on any pre-existing model or assumptions.

Results:
Figures 1, 2, and 3 confirm the large scatter in the amount of spontaneous imbibition by water for both the Tor and the Ekofisk formations. These figures also show that the water-wetness is neither controlled by porosity nor permeability nor the initial water saturation of the samples.
Using the same data, Figure 4 shows that the wettability to water is largely controlled by the height above individual free water levels (FWL). This result was the purest rule

achieved on the full data set (e.g. all results and all controls treated simultaneously) by the rule finding approach. The same conclusion was reached using the regression techniques on the largest available subset of data for each variable.

After that, attempts were made to explain the remaining scatter in the wettability results.
Initial Water Saturation: For each sample, the most likely initial water saturation in the reservoir was calculated from the Leverett's functions developed for the reservoir simulation model. It was found that a significant number of wettability tests have been performed with too high initial water saturations. These samples have been disregarded in the following when the discrepancy between the reservoir and the laboratory initial water saturation exceeds 10 saturation units. Figure 5 shows a much clearer trend in wettability versus depth when this constraint is applied. The relationship between wettability and depth is the same for both formations.

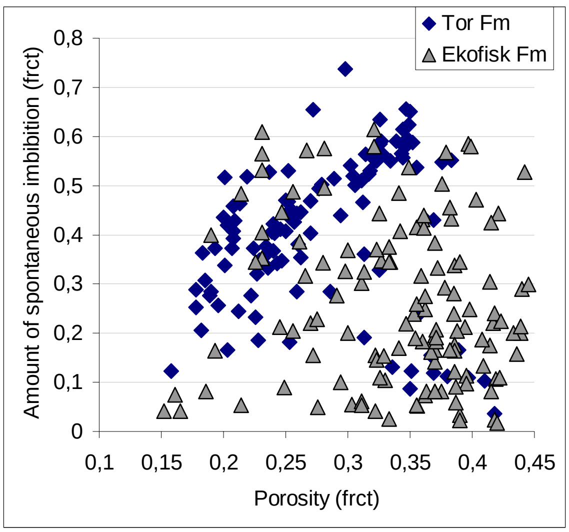


Figure 1 :Spontaneous imbibition as a function of porosity

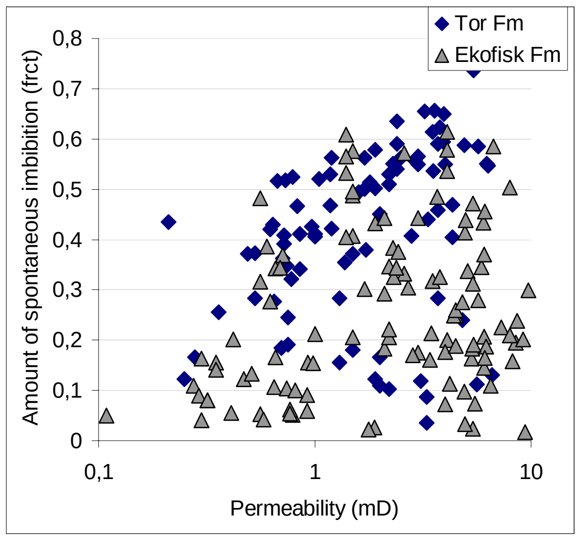


Figure 2 : Spontaneous imbibition as a function of permeability

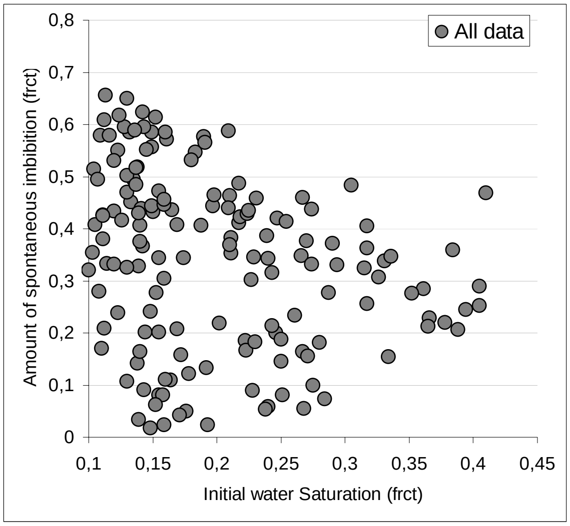


Figure 3: Spontaneous imbibition versus laboratory Swi

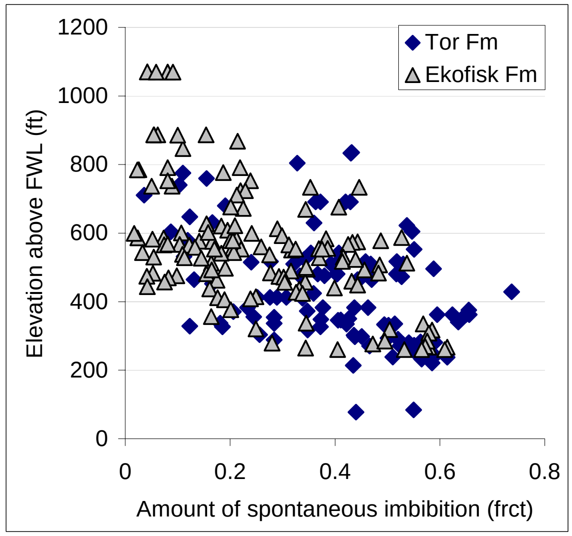


Figure 4: Spontaneous imbibition versus elevation above FWL

Type of Coring Fluid: Figure 6 shows the comparison between samples cored with water- and oil-base muds. Samples cored with water-base muds exhibit a clear trend in wettability versus depth, regardless of other variables. Samples cored with oil-base muds show a more scattered trend. As the vast majority of OBM samples were Soxhlet extracted, it is suspected that some of the samples have been contaminated by mud products and not properly cleaned. Therefore, the samples cored with OBM are deemed questionable.

Temperature of Wettability Tests: Figure 7 shows the comparison of spontaneous imbibition at different temperatures used during the wettability tests: reservoir, intermediate or ambient. There is a clear influence of temperature: the oil recovery by spontaneous imbibition increases when the temperature increases, as observed previously [1,5]. The relationship between wettability and depth holds whatever the temperature.

Core Preparation: Figure 8 shows the comparison of spontaneous imbibition after different core preparations: reservoir dead oil used after cleaning, reservoir or refined oil used for wettability tests without previous cleaning. Figure 8 does not show any major difference in the trend of wettability versus depth related to the core preparation.

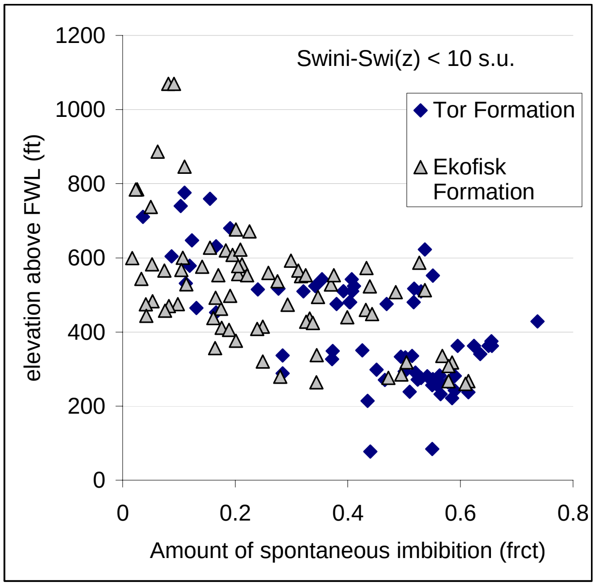


Figure 3: Spontaneous imbibition vs elevation above FWL

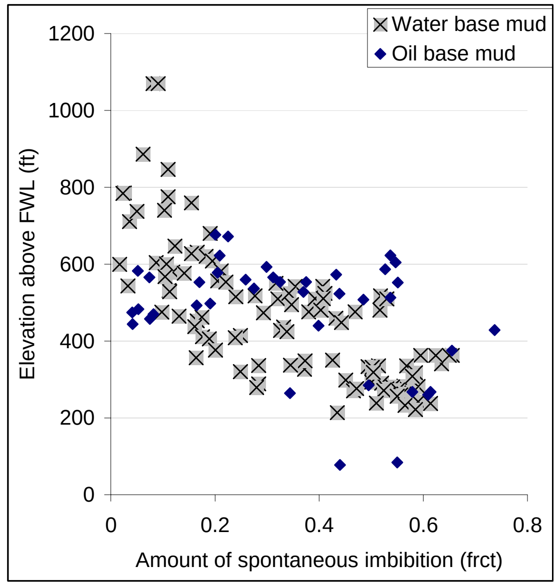


Figure 4: Effect of coring fluid on spontaneous imbibition

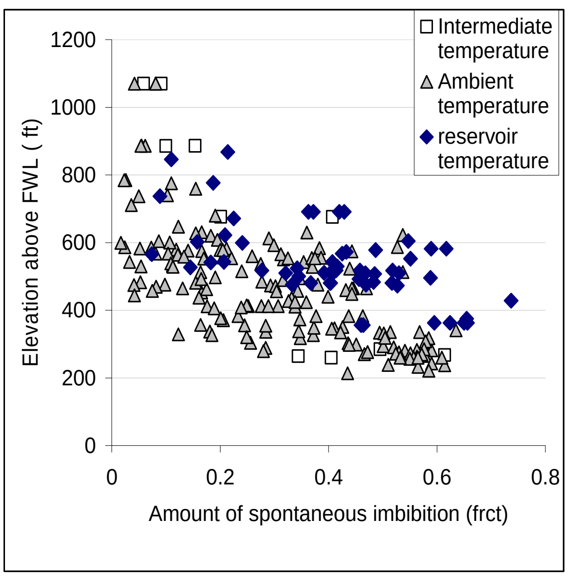


Figure 5 : Effect of temperature on spontaneous imbibition

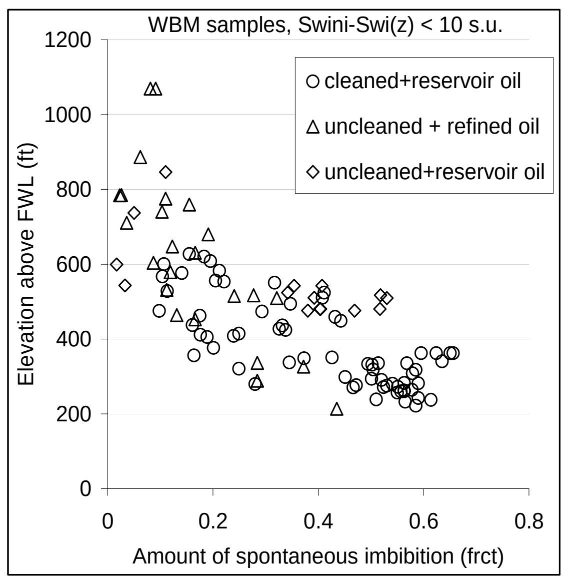


Figure 6 : Effect of core preparation on spontaneous imbibition

This data analysis shows that the water wetness varies significantly within the Ekofisk reservoir and is mainly controlled by the elevation above the free water levels. Near the water-oil contact (WOC), the samples are strongly water-wet. Higher up, the wettability

to water decreases. In the uppermost regions of Ekofisk, the water wetness is very weak. The Ekofisk and the Tor Formation behave very similarly. The scatter in wettability data, not explained by this main trend, is mainly linked to inappropriate initial water saturation at the start of wettability tests, and very likely to oil-base muds. There is a systematic effect of the temperature used for the wettability tests: water wetness increases with temperature. It has not been possible to show systematic shifts in wettability due to other parameters of the laboratory procedures.
Figure 9 illustrates a selection of wettability tests, including samples cored with water-base mud, which comply with the above criterion regarding initial water saturation. Neither porosity, permeability, or initial water saturation nor the formation controls the water wetness, despite the large range of rock characteristics covered by this selection. These conclusions are rather different from the early studies [2]. Figure 10 shows a clear trend of wettability versus depth on well 2/4-A8, the key well of the 1984 study, but this trend was not identified in the original study.

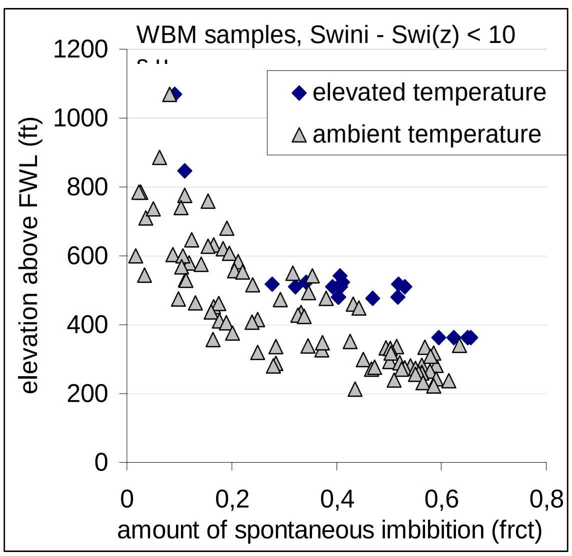


Figure 7: Wettability vs depth: final selection

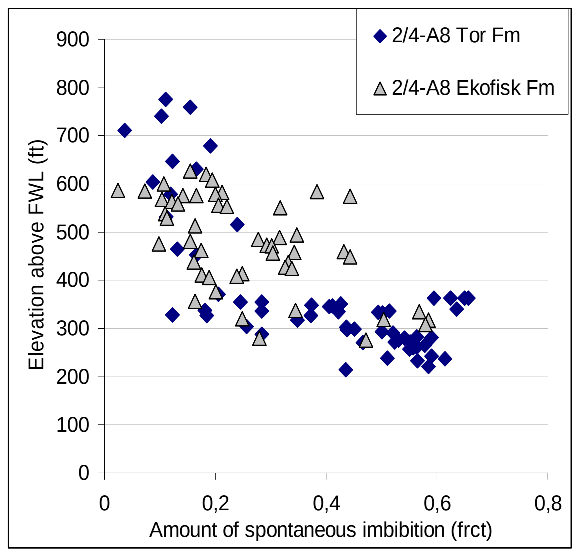
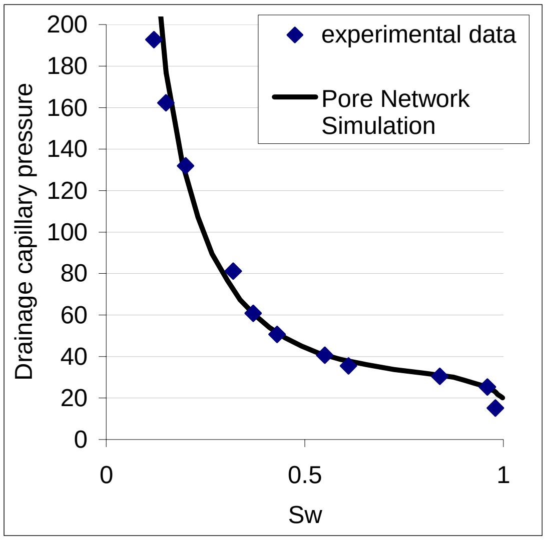


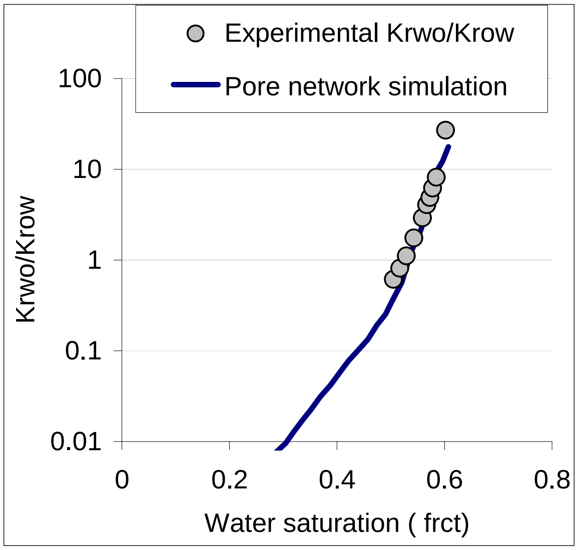
Figure 8: Wettability vs depth: 2/4-A8 well

MATRIX RELATIVE PERMEABILITY CURVES:

Matrix relative permeability curves are required to generate pseudo-Kr curves in both the extensively and sparsely fractured zones. The above results suggest that the matrix Kr curves should depend on the height above the contacts, and may be, also on the rock characteristics. But a review of the available laboratory waterfloods of the Ekofisk chalk area has shown that a limited number of corefloods is available. It is observed on this limited data set that the endpoint of the water relative permeability: Krwmax, increases as the elevation above the free water level increases. This result is consistent with the variation of wettability with depth: the rock ranges from strongly water-wet close to the contact to not water-wet at the top of the structure. However the range of variation of both the rock characteristics and depth was far from being covered by enough core floods on the reservoirs of the Ekofisk area. Thus, it has been decided to complement the existing Kr curves by curves generated by simulations of pore networks.

The pore network is anchored on three different types of information: 1)mercury injection capillary pressure curve, 2) the amount of spontaneous imbibition at a given height above the water-oil contact 3) the experimental water-oil relative permeability curves achieved on the deepest samples, e.g., at strongly water-wet conditions, for the same Pc rock-type. The two first anchoring data ensure that a sound representation of both the distribution of pore dimensions and of the wettability is embedded in the network model. The third type of anchoring data is required to constrain the model as recent studies showed that the match of the Pc curve was not unique [15, 16]. A detailed description of the pore network model used for this study is available in the literature [17, 18]. The MICP curve helps defining the distribution of pore entry radii and associated pore volumes. Reproducing the Kr curves at strongly water-wet conditions helps constraining the pore conductance and the coordination number. The simulation of the water imbibition tests at different depths is used to assess the fraction of oil-wet pores, the contact angles and the type of wettability distribution. Figure 11 shows the agreement between experimental and simulated drainage Pc curves. Figure 12 compares the experimental and simulated Krw/Krow curves, at strongly water-wet condition. Figure 13 shows the predicted variation of the maximum water relative permeability and of the residual oil saturation to water, for one Pc rock-type. This figure shows that the residual oil saturation to water decreases and the maximum water relative permeability increases as the amount of spontaneous imbibition decreases.





Comparison between experimental data and pore network simulation

Figure 9 : Capillary pressure

Figure 10 : water/oil relative permeability curves

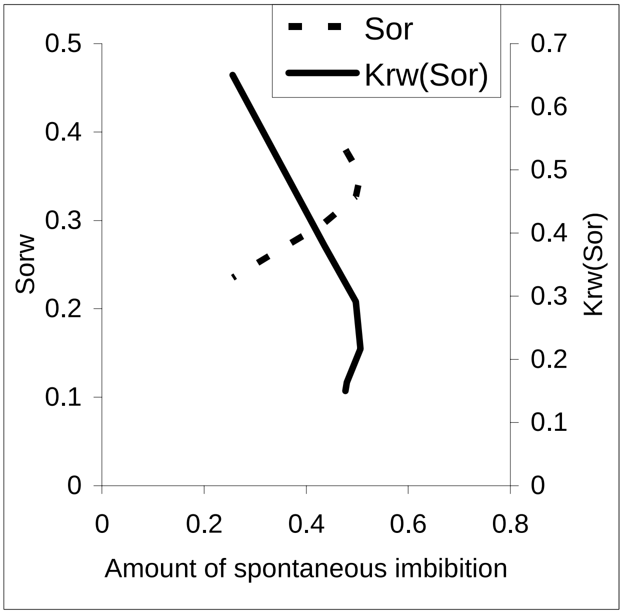


Figure 11 : Pore Network Simulations

DISCUSSION:

This study illustrates that a strong relationship exists in the Ekofisk field between the wettability and the elevation above the free water level. This result is consistent with recently published data [14, 19-21], showing a clear tendency of increasing water-wet characteristics with depth in both sandstone and carbonate reservoirs. Trends in endpoint water relative permeability in Ekofisk are also in agreement with the evolution of wettability with depth, as previously shown for some sandstone reservoirs [22,23].

This study also shows that the wettability may range from strongly water-wet to not water-wet within the same reservoir. This large variation cannot be explained by variations in the mineralogy or the oil composition, as no systematic depth trend in mineralogy nor oil composition (no depth variation of the parameters for the representation of the fluid by an equation of state) has been identified.

It might indicate that this variation is largely caused by the decrease in water saturation and the increase in capillary pressure as the height above the free water level increases. This large variation of wettability index within a reservoir raises issues about the relationship between the different approaches used to assess the wettability and particularly between the contact angle methods and the displacement techniques, such as the Amott-Harvey or USBM tests. The former has often been used to obtain a “single” wettability for a reservoir [24] whereas the latter give increasing evidence of large variations of wettability indexes within a reservoir [14, 19-21]. These two approaches have widely different consequences in sampling for core floods or in simulation model inputs, as pointed out in [23].

An interesting feature of this study is the existence of a strong relationship between the water wetness and the elevation above the FWL whatever the core preservation technique (fresh or cleaned, restored or not) or the other tests characteristics (imbibition at room or elevated temperature). This is particularly amazing for cleaned samples (see figure 8), provided that they were cored with water-base muds. Even if this observation might be field dependent, it indicates that such reservoir trends are sometimes robust enough to survive despite widely different laboratory procedures.

Regarding the effect of wettability and viscous forces in naturally fractured reservoirs, Tang and Firoozabadi [25] stated recently that “the recovery from the chalk reservoirs may be nearly independent of the wettability state” and “the results from the experiments also reveal that there is no relationship between laboratory measurements of spontaneous imbibition and field performance of mixed-wet reservoirs”. Both statements are incorrect. Their first conclusion would imply that all fractured reservoir exhibit the same good performance as Ekofisk waterflood. This first statement is not confirmed by several field cases showing poor waterflood efficiency in fractured chalky carbonate reservoirs [26] or sandstone reservoirs [27]. The second statement is not supported by the results presented in their own paper [25]. The oil recovery by spontaneous imbibition on mixed wet case (referred as 500 ppm stearic acid) ranges from 39% to 48.5%. For the same wettability conditions, the final recovery achieved by waterflooding at 0.02 psi/cm a fractured stack of samples ranges from 44.7 to 47%, showing no improvement compared to the spontaneous imbibition case. The comparison with the water-wet case shows a very significant difference, with oil recovery equal to 66%, both by spontaneous and forced imbibition. It seems that Tang builds his second conclusion on the recovery achieved at high rate waterflood of the fractured composite core: ranging from 60 % to 62.6%.

Unfortunately, this test is performed at a very high pressure gradient: 0.1 psi/cm. Such a pressure gradient is experienced either in the near wellbore area for high permeability fractured reservoirs, not in the far wellbore area and then concerns a limited volume of oil or in very sparsely fractured, tight zones.

It is clear today that the Ekofisk waterflood performance is a combination of capillary imbibition and viscous displacement. In fact, the local performance of the waterflood in a fractured reservoir strongly depends on fracture characteristics and wettability. Both will influence the pseudo relative permeability used in a single porosity model to represent Ekofisk [9]. In the most permeable, fractured zones, the overall behaviour will depend on the fracture spacing, and the combination of spontaneous imbibition and weak viscous drive, mainly through the imbibition capillary pressure and water breakthrough has been observed in areas of Ekofisk not consistent with expectations [9]. In the low permeability, sparsely fractured areas the matrix relative permeability will be a major control of the waterflood performance as the viscous drive prevails; matrix Kr curves have long been known to be dependent on wettability and thus should depend on depth.

CONCLUSIONS:

The review of 250 wettability tests on Ekofisk has shown:

- A very large scatter in wettability index to water: ranging from strongly water-wet to neutral. Part of this scatter is shown to be due to inappropriate coring fluid (oil-base muds) and initial water saturation.
- Once these tests are disregarded, the relationship between the elevation above the original WOC and the wettability index appears to be a major control for both Ekofisk wettability,
- A clear tendency of increasing water-wet characteristics with depth,
- The survival of a strong relationship between depth and wettability on cleaned samples illustrates that this trend is very robust,
- The relationship between depth and wettability has been identified directly as the key effect by data mining techniques (i.e. regardless of any understanding of the physical processes) as well as by reducing the data set based on previous expertise.
- Once the key reservoir controls have been identified, the secondary effects of laboratory procedures can be seen, particularly the effect of temperature during imbibition tests

Matrix water-oil relative permeability curves have been generated using pore network modelling. This approach allowed incorporating the variations of both the rock characteristics and of the depth-dependent wettability and complements the experimental core floods when no data is available for a given combination of lithology and wettability.

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