A NEW METHOD TO NORMALIZE CAPILLARY PRESSURE CURVES

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ABSTRACT

A new method for normalizing capillary pressure curves has been developed for North Sea chalks. The new method includes explicit functions for the irreducible water saturation (Sw_{ir}), the capillary entry pressure (Pce) and the capillary shape function. It provides a complete capillary pressure model and allows the prediction of both saturation-height functions and the free water level (FWL).

The basic functions in the model can be derived from capillary pressure tests on core material. The model is calibrated to actual reservoir conditions by adjustment of one single calibration constant.

This paper presents the new method (basic theory and equations) and illustrate the basic capillary pressure functions for the Danian and Maastrichtian chalks in the Danish part of the North Sea. The validity of the new model is demonstrated by a comparison of log inferred and model predicted saturations in two cases: One where both the oil water contact (OWC) and the FWL could be established independently and one where only the saturation profile could be inferred from logs.

INTRODUCTION

Oil and gas reservoirs in the Danish part of the North Sea are typically found in high porosity, low permeability, Cretaceous chalk of Danian and Maastrichtian age. The porosity of the reservoir chalks ranges from 20 to 50% while the liquid permeability ranges from 0.02 to 5 mD. Capillary effects in the chalks are often very significant, and the capillary transition zone in the chalk reservoirs ranges from 100 ft to more than 500 ft. Construction of accurate capillary pressure models applicable for Danish chalk reservoirs is therefore very important (long transition zone) and difficult (large variations in rock properties).

A capillary model is constructed by normalization of core data or log data (or both). The objective of this process is to extract an un-biased model that allows an accurate prediction of the capillary properties for the entire range of rock types, porosities and capillary pressures to be found in the reservoir.

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The normalization of the capillary pressure data is traditionally done using the Leverett J-function[1], the Thomeer function[2], the Heseldin method[3], the CapLog method[4] or other similar methods. The applicability of these methods has also been tested on chalk data. It was, however, found that given the explicit or implicit assumptions underlying the methods, for example:

o Pce is proportional to $(\phi/K)^{0.5}$ and Sw_{ir} is constant (Leverett J-Curve[1]).

o the capillary shape curve can be modelled by an exponential decay function (Thomeer[2] function).

o the capillary pressure curve can be expressed as a displaced rectangular hyperbola (Heseldin[3] medthod).

o Pce varies exponentially with ϕ, Sh is proportional to $\log(FWL-D)/\phi$ and Sw_{ir} is undefined (CapLog[4] method).

it was not possible to model the capillary pressure behaviour for a given chalk formation (Danian or Maastrichtian) across the entire range of porosities and capillary pressures typically found within the Danish chalk reservoirs.

A new normalization method was therefore developed. The objective for the new method was to ensure that

o any explicit function for Sw_{ir}, Pce and capillary shape based upon laboratory test data can be included in the model,

o the model will provide physical meaningful results across the entire range of possible capillary pressures and porosities and

o the physical meaning of Pce, Sw_{ir} and capillary shape curve in the model is apparent.

CAPILLARY PRESSURE MODELLING

Objective

The objective of capillary pressure modelling is to obtain simple analytical expressions that either relate the connate water saturation (Sw) to the height above the FWL (forward modelling) or relate the height above the FWL to the connate water saturation (reverse modelling). Any analytical procedure is considered to be a good model if the observed difference between 'predicted Sw' and 'actual Sw' is small for all relevant reservoir conditions (i.e. range of capillary pressure and rock types encountered in the reservoir).

Fundamental Equations

The fundamental equations for a capillary pressure model express the relationship between the capillary pressure (Pc) and the wetting phase saturation (Sw) at reservoir conditions (Eq. [1] and [2]). The functions $f_1(Pc)$ and $f_2(Sw)$ are ideally true inverse functions, and have to be defined either by normalization of core data or of log data (or both).

$$Pc = (D - FWL) \times \Delta\rho_{w-h} \iff FWL = Pc/\Delta\rho_{w-h} + D \qquad [1]$$

$$Sw = f_1(Pc) \text{ and } Pc = f_2(Sw), \text{ ideally } Sw = f_1(f_2(Sw)) \qquad [2]$$

Reference System

All the basic parameters and functions in Eq. [1] to [2] have to be defined for the specific reservoir conditions considered. However, in the case of intrinsically water wet reservoirs with rock types containing only limited volumes of minerals with surface bound water (e.g. clays), then the functions $f_1(Pc)$ and $f_2(Sw)$ may be defined from laboratory tests at any conditions, provided that Eq. [1] and [2] are changed as indicated by Eq. [3] to [5]. This is so because the capillary pressure at any given water saturation for these rock types is proportional to the effective surface tension ($\sigma \times \cos(\theta)$) for the rock-fluid system.

$$Pc_l = (D - FWL) \times (\Delta\rho_{w-h} \times C_{r\rightarrow l}) \iff FWL = Pc_l/(\Delta\rho_{w-h} \times C_{r\rightarrow l}) + D \qquad [3]$$

$$Sw = f_1(Pc_l) \text{ and } Pc_l = f_2(Sw) \qquad [4]$$

$$C_{r\rightarrow l} = (\cos(\theta_l) \times \sigma_l)/(\cos(\theta_r) \times \sigma_r) \qquad [5]$$

Danian and Maastrichtian North Sea chalk consist predominantly of calcite with only minor volumes (2-5%) of insoluble residue (clays, silica etc.). Furthermore, Amott wettability tests have indicated that chalk is water wet prior to the intrusion of oil into the pore space. Eq. [3] to [5] can therefore be considered to be valid for the Danish North Sea chalk reservoirs.

The fluid density difference ($\Delta\rho_{w-h}$) can be defined by either PVT-analysis or formation pressure analysis. "$C_{r\rightarrow l}$" can in principle be determined from two measurements of the effective surface tension: One at laboratory conditions and one at reservoir conditions. This is rarely done in practice, however, and the effective surface tension is often just inferred from correlations and average laboratory data. The accuracy of "$C_{r\rightarrow l}$" is therefore often not better than +/- 50%. Practical experience, however, has illustrated that the low accuracy of "$C_{r\rightarrow l}$" has no practical consequences for the construction of an accurate capillary pressure model because a sufficiently accurate value for the product "$\Delta\rho_{w-h} \times C_{r\rightarrow l}$" can be obtained from a calibration of the capillary pressure model to log data.

Practical Laboratory Fluid-Systems

In principle, any fluid system, test temperature, tests pressure etc. can be used to establish the functions $f_1(Pc_i)$ and $f_2(Sw)$. Nevertheless, in the case of chalk only the air-Hg system can be used in practice.

This is so because practical experience with capillary pressure testing of chalk samples has illustrated that the time required to obtain drainage capillary equilibrium for a chalk sample with water as the wetting phase may vary from weeks to months. The long equilibration time for chalk is a consequence of a combination of low drainage relative permeability to water ($Kr_w < 0.001$ for $Sw < 20\text{-}30\%$), low absolute liquid permeability (0.02-5 mD), high porosity and low irreducible water saturation (typically 5% or less for high porosity chalk).

A long equilibration time for chalk with water as wetting phase is therefore unavoidable, and the required equilibration time at each pressure step is nearly always significantly longer than practically or economically acceptable. The accuracy of recorded oil-brine or air-brine capillary pressure curves on chalk samples must therefore generally be questioned.

CAPILLARY PROPERTIES OF CHALK

Basic capillary properties of the Danian and Maastrichtian chalks have been derived from reviews of almost 1000 capillary pressure curves that presently exist within the Mærsk Oil database. This large data set includes air-Hg (wetting phase is in reality Hg-vapor), air-brine and oil-brine capillary pressure curves recorded using the mercury intrusion, porous plate and centrifuge techniques.

The number of data points in the older capillary pressure tests (Figure 1a) are often insufficient for any given test alone to define the capillary entry pressure and irreducible wetting phase saturation accurately. This is not the case for the more recent tests (Figure 1b). Review of the large data set has led to following general observations:

o   Danian and Maastrichtian chalk have different capillary properties. The observed differences are most likely due to differences in the size and shape of the Danian and Maastrichtian coccoliths.

o   Chalks of the same age (Danian or Maastrichtian) have close to the same capillary properties across the Danish part of the North Sea for any given porosity.

o   Capillary pressure curves are very sharp, indicating a narrow and unimodal pore throat size distribution for chalk.

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o   Capillary entry pressure increases gradually with decreasing porosity.

o   Irreducible water saturation (assumed = Sw(2000 psi Hg-pressure)) increases gradually with decreasing porosity. Irreducible wetting phase saturation for the air-Hg system is in agreement with inferred irreducible water saturation from logs. This supports the validity of Eq. [3]-[5] for chalk.

o   Air-brine and oil-brine capillary pressure curves may produce accurate estimates of the capillary entry pressure, but must be considered generally to yield too high estimates of the irreducible water saturation because capillary equilibrium is not achieved at each pressure step.

o   Capillary entry pressure for any given chalk formation is more closely related to the total porosity than to single phase permeability. Porosity is therefore a better input parameter for capillary pressure modelling than permeability.
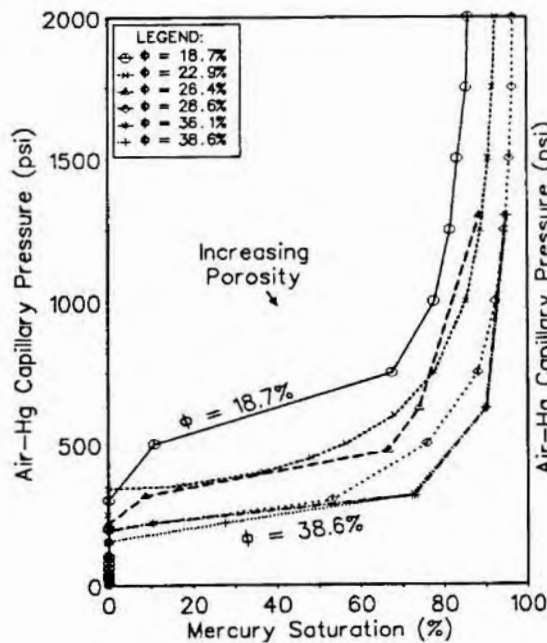
Figure 1a: Old Air-Hg Pc-curves
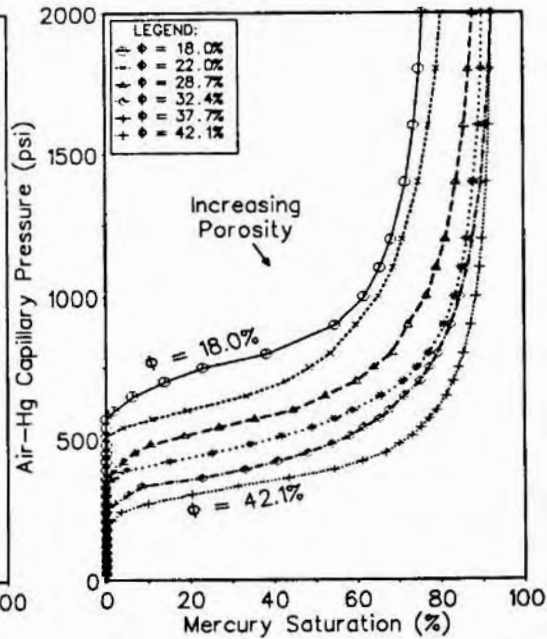   Danian Chalk

Figure 1b: Newer Air-Hg Pc-curves
            Maastrichtian Chalk

The main conclusions of the reviews were that

o   any successful capillary pressure model for chalk has to take explicitly into account the gradual changes in the capillary properties in response to changes in porosity.

o   existing capillary normalization methods cannot predict the capillary properties of a given chalk formation (e.g. Danian or Maastrichtian). The Leverett[1] J-curve is e.g. not capable of predicting the increasing Sw_{ir} at low porosities (Figure 2) or the actual slope of the Pce-ϕ correlation (Figure 3), while the Thomeer[2] function is not capable of modelling the actual capillary shape function (Figure 4).

EQUIVALENT RADIUS METHOD

In recognition of the importance of an improved capillary pressure model for chalk, an in-depth study of the possibility of designing a special normalization procedure valid for chalk was initiated. The result of this study was a new normalization procedure called the "Equivalent Radius" or EQR-model.

Definition of Model

The EQR-model is based the upon following basic observations:

o   Capillary entry pressure for chalk increase gradually as function of decreasing porosity.

o   Irreducible wetting phase saturation increase gradually with decreasing porosity.

o   Shape function for the drainage capillary pressure curve seems independent of porosity for a given chalk type.

o   Capillary pressure seems more related to porosity than to permeability.

These basic observations led to the following basic rules for the EQR-model:

o   Porosity effects to be modelled by a porosity dependent function for irreducible water saturation ($Swir = f_3(\phi)$) and a porosity dependent function for the capillary entry pressure ($Pce = f_4(\phi)$).

o   Effect of pore throat size distribution to be modelled by a shape function ($Snw' = f_5(EQR)$ or $EQR = f_6(Snw')$) that relates normalized non-wetting phase saturation ($Snw' = (1-Sw)/(1-f_3(\phi))$) and equivalent radius ($EQR = f_4(\phi)/Pc_l$).

Analytical Implementation of Model

Following simple analytical model satisfies all the basic observations for North Sea chalk and constitutes a complete capillary pressure model that provide physical meaningful results for all posible combinations of rock type, porosity and capillary pressure or height above FWL (D-FWL):

Forward modelling:

$$Pc_l = (D - FWL) \times (\Delta\rho_{w-h} * C_{r\to l}) \qquad [6]$$

$$EQR = f_4(\phi)/Pc_l \qquad [7]$$

$$Snw' = f_5(EQR) \qquad [8]$$

$$Sw = 1-Snw' \times (1-f_3(\phi)) \qquad [9]$$

Reverse modelling:

$$Snw' = (1-Sw)/(1-f_3(\phi)) \qquad [10]$$

$$EQR = f_6(Snw') \qquad [11]$$

$$Pc_l = f_4(\phi)/EQR \qquad [12]$$

$$FWL = Pc_l /(\Delta\rho_{w-h} \times C_{r\to l}) + D \qquad [13]$$

The analytical implementation of the EQR-model requires that laboratory tests can define the basic capillary functions ($Sw_{ir} = f_3(\phi)$, $Pce = f_4(\phi)$, $Snw' = f_5(EQR)$, $EQR = f_6(Snw')$) for each of the penetrated chalk types and that calibration of the model to log data can provide the constant "$\Delta\rho_{w-h} \times C_{r\to l}$" for a given reservoir.

Laboratory Calibration of EQR-Model

The basic capillary pressure functions for Danian and Maastrichtian North Sea chalks have been generated by plotting normalized air-Hg capillary pressure data using an iterative procedure that allow Pce, Sw_{ir} and shape function to be changed for a given sample until the scatter around the correlation lines for all the samples in a dataset is minimized and an internally consistent set of basic functions has been generated.

The results of the iteration procedure performed on a set of 14 drainage capillary pressure curves recorded on Danian chalk can be viewed on Figures 2-4. Figures 2-4 also include the average Danian and Maastrichtian correlations based upon a larger data set.
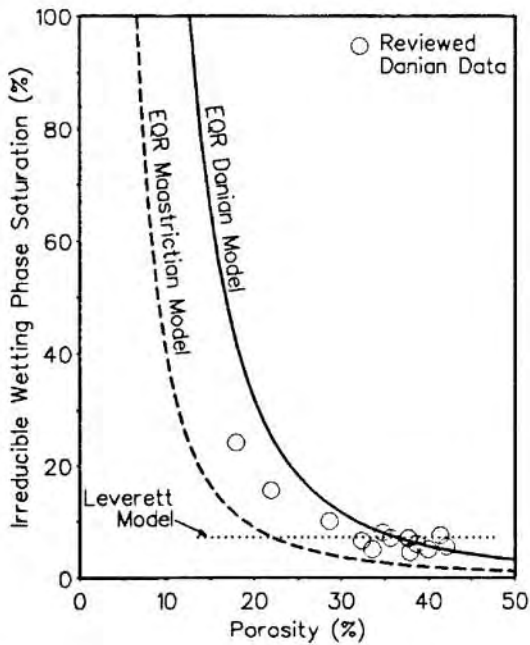
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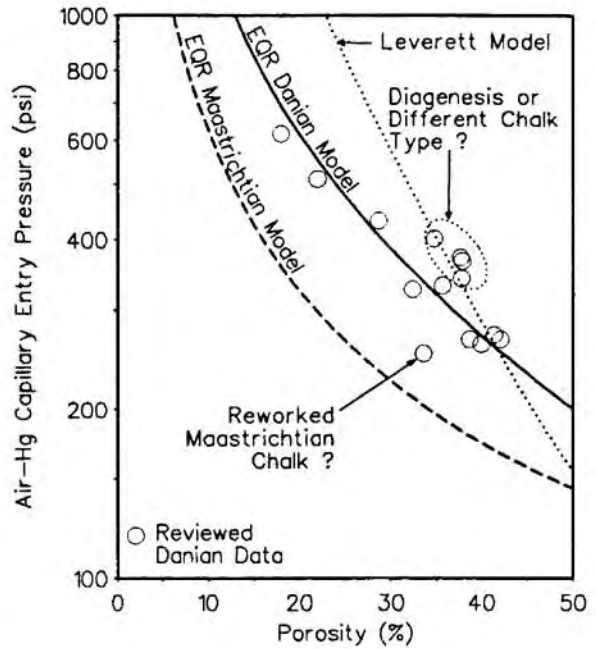Figure 2: Irreducible Water Saturation vs Porosity, Danian Chalk Data

Figure 3: Capillary Entry Pressure vs Porosity, Danian Chalk Data

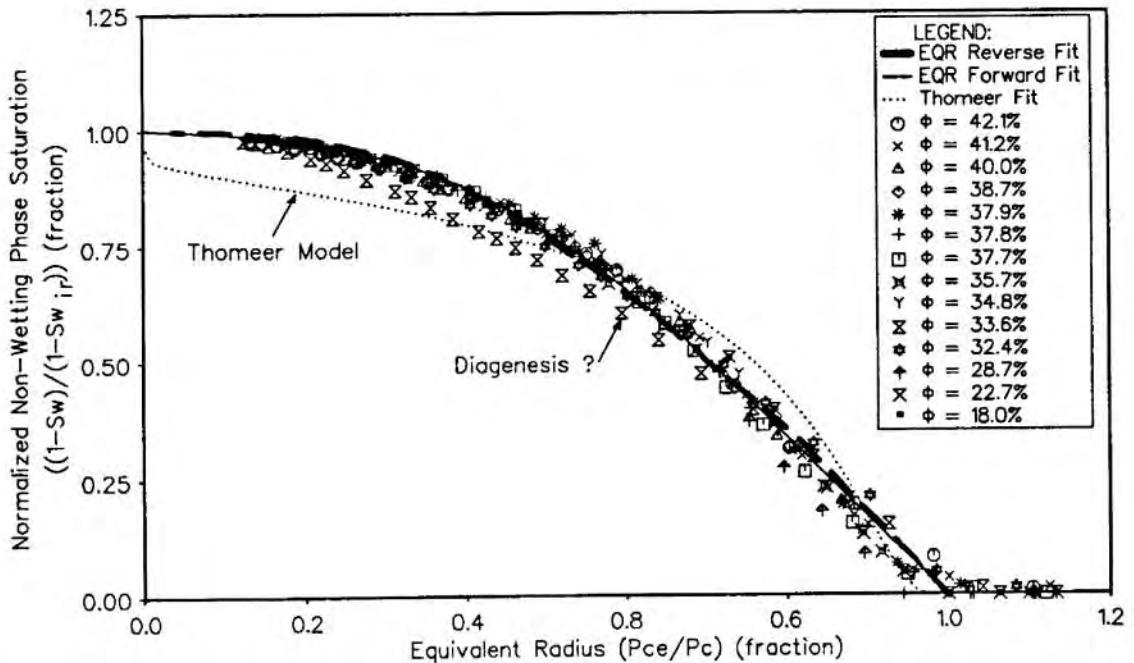Figure 4: Normalized Non-wetting Phase Saturation vs Equivalent Radius

Figures 2-4 indicate that:

o   Irreducible wetting phase saturation for chalk is low and the correlation between Sw_{ir} and ϕ can be considered well defined. Uncertainty on Sw_{ir} is typically less than 5% (Figure 2). Future updates of the Danian EQR-model may further reduce the uncertainty on the Sw_{ir} prediction for a given dataset.

o   Capillary entry pressure is clearly correlated to porosity (Figure 3). However, some of the data points deviate 25-30% from the general Pce-ϕ correlation for Danian chalk. Attempts to explain the deviations as samples with unusual permeability, rock type etc. were partly unsuccessful.

o   Normalized non-wetting phase saturation is well correlated to EQR (Figure 4).

Experience has indicated that $f_5(EQR)$ can be expressed as a polynomium of EQR, while $f_6(Snw')$ can be expressed as a polynomium of log(1-Snw') in the case of Danish North Sea chalk. $Sw_{ir} = f_3(\phi)$ and $Pce = f_4(\phi)$ can be expressed as displaced powerfunctions.

Calibration of Model using Log Data

The final calibration of the EQR-model requires a determination of "$\Delta\rho_{w-h} \times C_{r\rightarrow l}$". This is done by a comparison of the predicted saturation profile to the actual saturation profile derived from logs. In the cases where both the OWC and FWL can be defined from log data a sufficiently accurate estimate of "$\Delta\rho_{w-h} \times C_{r\rightarrow l}$" can be obtained by matching the predicted capillary entry height to the actual capillary entry height for the reservoir (forward modelling). In the cases where neither a FWL nor an OWC can be extracted from the log data because only the hydrocarbon bearing part of the reservoir has been logged, a sufficiently accurate estimate of "$\Delta\rho_{w-h} \times C_{r\rightarrow l}$" can be obtained by interactively adjusting the value of "$\Delta\rho_{w-h} \times C_{r\rightarrow l}$" in the model until the predicted FWL is independent of depth (reverse modelling).

TEST OF EQR-MODEL

The EQR-model has been tested on a number of the Danish chalk reservoirs including both cases where the FWL and OWC could be defined from logs and cases where they could not. An example of each case is given in the following.

The well in **example no 1** (Figure 5) penetrates a thin Danian and a thick Maastrichtian chalk sequence. The saturation profile, and the OWC and FWL for the well were defined by standard log analysis. Logged oil saturation and the modelled oil saturation profile were matched by first generating the four basic capillary functions for the Danian and Maastrichtian chalks and then obtaining the value for "$\Delta\rho_{w-h} \times C_{r\rightarrow l}$" by matching the OWC/Oil-down-to (ODT) predicted by model to the actual OWC/ODT inferred from logs.
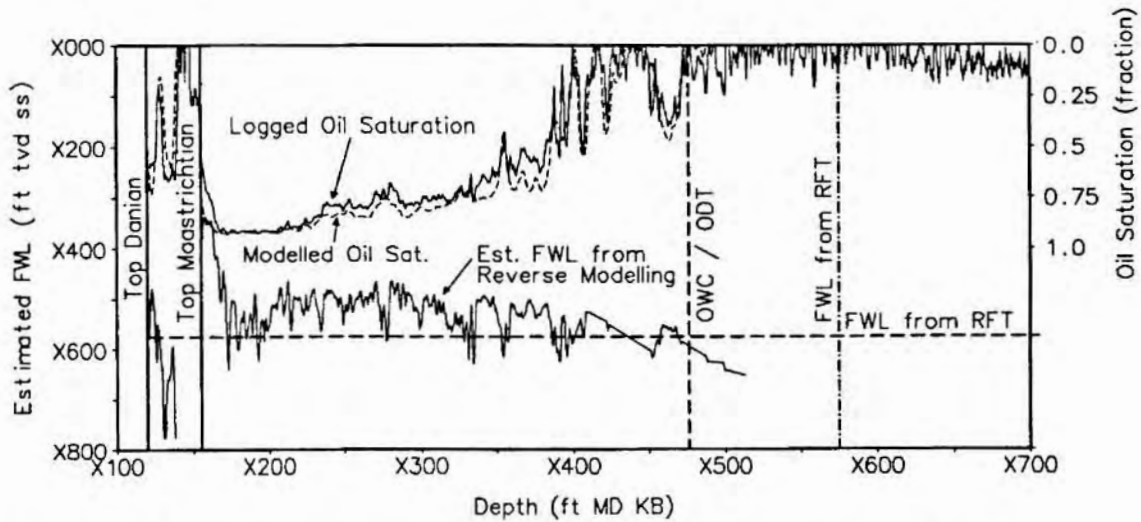
Figure 5: Logged and modelled oil saturation vs depth . Fixed OWC and FWL.

The well in **example no 2** (Figure 6) penetrates a relatively thin Danian and Maastrichtian chalk sequence above an interval of non-reservoir rock. Within both the Danian and the Maastrichtian sections a significant variation in porosity with depth was observed and the penetrated chalk sequence contained several intervals of low porosity non-reservoir chalk with no oil saturation.

The objective for the EQR-model in example no 2 was to obtain a realistic estimate of the FWL below the base of the chalk reservoir. This estimate was obtained by adjusting the value for "$\Delta\rho_{w-h} \times C_{r\rightarrow l}$" until the predicted FWL by the model was independent of depth.
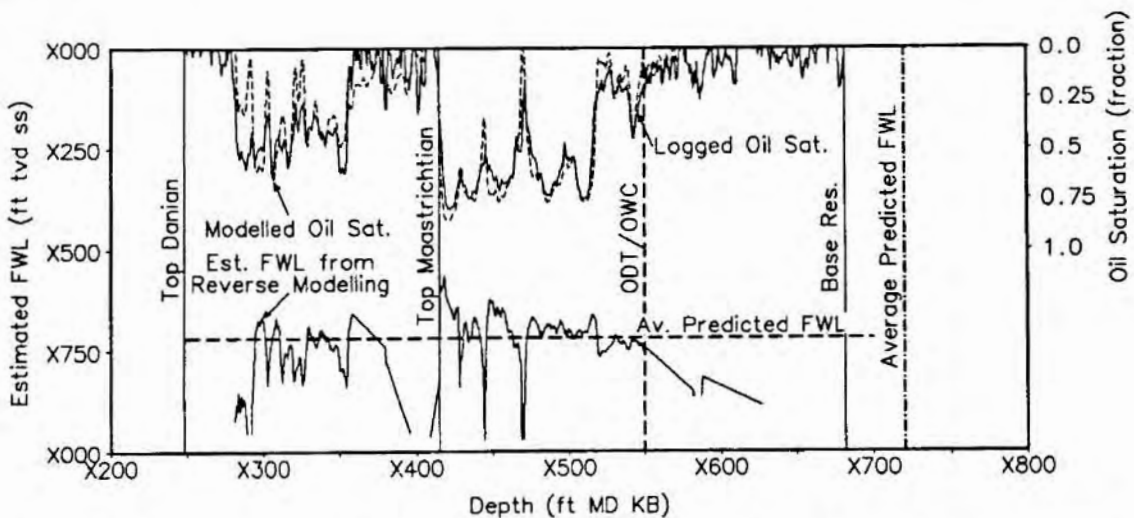
Figure 6: Logged and modelled oil saturation vs depth. FWL below base reservoir.

DISCUSSION

Although the remaining small differences between logged and modelled saturations could be due to uncertainty in the EQR-model they may equally well be due to a systematic error in the log analysis. The agreement between modelled and logged saturations in Examples 1 and 2 is therefore taken as an indication that the EQR-model can be used to generate accurate saturation-height models for Danish North Sea chalks.

The main source of remaining uncertainty in the EQR-model is the variation in capillary entry pressure for a given chalk porosity and formation. The observed variability is typically equal to a 25% uncertainty on the capillary entry height and is at present considered related to variations in the basic rock properties. The uncertainty can therefore only be removed/reduced if a subdivision of chalk types can be found allowing chalk types with high/low capillary entry pressure for a given porosity to be separated. In order to make such a subdivision practically applicable it need to based upon log responses. Various attempts have been made to classify the samples with an unusual high/low capillary entry pressure. These attempts have, however, not yet been fully successful, although it has been found that Danian samples with an unusual low Pce could often be classified as re-worked Maastrichtian chalk (Figure 3).

The EQR-method was originally designed as a special capillary normalization method for Danish North Sea chalks. The EQR-method is, however, generally applicable to all rock types that do not contain any significant amounts of surface bound water, where all the basic capillary pressure properties are more related to porosity than to any other basic rock parameter (e.g. permeability) and where the normalized porethroat distribution function is relativ independent of rock type.

CONCLUSIONS

Practical experience with the EQR-model has illustrated that this model is capable of accurately predicting the capillary properties of chalk in the Danish part of the North Sea and that the EQR-model can be used to predict the depth of the FWL in those cases where only the saturation profile exists.

ACKNOWLEDGEMENTS

NOMENCLATURE

Symbols

C	Capillary pressure conversion factor
D	Depth (tvd)
EQR	Equivalent Radius
FWL	Free Water Level
K / Kr	Permeability / relative permeabity
OWC / ODT	Oil Water Contact / Oil Down to
Pc,Pce	Capillary pressure, capillary entry pressure
Snw'	Normalized non-wetting phase
Sw	Wetting phase or water saturation
Sh	Hydrocarbon saturation
Swir	Irreducible wetting phase saturation
ϕ	Porosity
$\Delta\rho$	Fluid density difference
θ	Wetting angle
σ	Surface tension

Functions $f_1(\phi)$, $f_2(\phi)$, $f_3(\phi)$, $f_4(\phi)$, $f_5(EQR)$ and $f_6(Snw')$

Subscripts

$r \rightarrow l$	Reservoir system to laboratory system
w-h	Water density minus hydrocarbon density
w	Water

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