INTEGRATION OF WATER/OIL CAPILLARY PRESSURES FROM DIFFERENT MEASUREMENTS IN A COMMON CAPILLARY PRESSURE MODEL FOR AN EXTREMELY HETEROGENEOUS CARBONATE RESERVOIR (CASE STUDY)

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ABSTRACT
A novel modelling approach was adopted to integrate the water-oil capillary pressure data in a complex, extremely heterogeneous carbonate reservoir. A proper description of the measured capillary pressures is a critical input into detailed reservoir modelling, describing the reservoir at centimetre scale. The primary objective of this detailed modelling was to understand the distribution of remaining oil in the reservoir, estimate potential recoveries through conventional means and test new recovery schemes to improve recovery. The secondary objective was to derive effective properties to ensure the main impact of fine-scale heterogeneity (at cm-scale) is captured in dynamic model.

Some 50 centrifuge capillary pressure curves were available. An equal number of Mercury Injection Capillary Pressure (MICP) curves as well as saturation data from logs were also used. The capillary pressure curves were described using a pseudo Corey model as proposed by Masalmeh, S. et al., (2006). Curves from centrifuge and MICP were all integrated and used in the modelling process. Parameterization when possible was done to aid the modelling exercise. The capillary pressure model allows imbibition curves to be calculated from drainage curves using the drainage and imbibition contact angles. The imbibition contact angle was derived from samples where both drainage and imbibition curves are available. The matching of capillary pressure with permeability and rock type derived models with measured data looks reasonable given the extremely complex reservoir architecture.

This paper will highlight the validation process, the approach taken to classify each principal rock types, the modelling method of respective capillary pressure curves and steps taken to generate the capillary pressure models.

INTRODUCTION
The reservoir studied consists of fractured, shallow carbonates in the Natih formation, and is a major oil-producing reservoir in Oman. It has a strong dip (15^{o}), high relief structure and contains a light, low viscosity and low Gas-Oil-Ratio oil. The large scale reservoir

architecture is layered cake type but consists of a succession of transgressive and regressive depositional cycles. The reservoir is generally fractured and features a high porosity but with low matrix permeability. However, significant internal heterogeneity occurs from the plug scale (cm) to the scale of the major flow units (10-100m), which make up the reservoir. The fracturing is also varied in terms of fracture density, direction and fracture permeability. The field is developed through a mixture of Gas-Oil-Gravity-Drainage (GOGD) and Water Injection (WI) over the course of its 40-year life. Currently studies are underway to evaluate alternative (EOR) development options.

Reservoir performance analysis and detailed reservoir simulation have shown that both matrix and fracture heterogeneity are major factors in explaining historic performance and predicting the future performance for the development options under consideration. Capillary pressures are a key property that impacts both matrix flow and matrix - fracture interaction. As part of the reservoir characterization studies a Special Core Analysis (SCAL) program was performed looking at capillary pressures and relative permeabilities for Water-Oil and Gas-Oil systems, covering both drainage and imbibition. This paper is limited to Water-Oil capillary pressures and focuses on the quality checking of the SCAL experiments and the application of a capillary pressure model to describe the experimental results. It also briefly discusses data coverage and plug selection.

PLUG SELECTION AND CHARACTERIZATION

The characterization of the rock matrix relies on adequate core and log data. Although over 20 wells had been cored until 2003, the core recovery was limited to the tighter and more competent stratigraphic units. SCAL using state-of-the-art techniques was available only in a few layers in two wells restricted to the North-West corner of the field (see Figure 1). Log data was available for many wells, however no comprehensive suite of logs was available for the cored wells.

Consequently, an extensive coring and logging campaign was executed in the years 2003 to 2005. Complete coverage of all major stratigraphic intervals was achieved, while the availability of cores from multiple wells also provided lateral control (Figure 1).

The SCAL plug selection was based on a screening process using a combination of core description, thin section, MICP, pore throat distribution and Computed Tomography (CT) scans. This process reduced the data set from about 5100 routine plugs to some 233 representative samples for SCAL analysis. Failures during SCAL experiments due friable nature of the rock reduced the number of samples available for static and dynamic data evaluation further to 167. Of these, 87 data are available for determining relative permeability, residual oil saturation and connate water saturation, while the other 80 samples were used to measure cementation factor (m), saturation exponent (n), wettability and NMR properties (Mookerjee, A. and Alias, A., 2006). The remaining data set is actually unusually large and of a quality not commonly available in carbonate reservoirs.

At the lowest level the reservoir is subdivided into Primary Rock Types (PRT A, B, C, D and E) based on extensive plug and thin section analysis. Each PRT is linked to digenetic phenomena such as cementation and leaching (Figure 2) and covers a range of porosity and permeability, capillary pressures and relative permeabilities. Figure 3 shows a poro-perm plot with distribution ranges for PRT A, B, C, D and E. In order to link capillary pressures (and relperms) to PRTs, each SCAL plug has been linked to a specific PRT. This was only possible if one of the PRTs was dominantly present in the plug.

CAPILLARY PRESSURE MEASUREMENTS AND QUALITY CHECKING

In this paper three types of capillary pressure measurements are discussed:

- Mercury (air) Injection Capillary Pressures (MICP) primary drainage measurements
- Oil - Water primary drainage centrifuge measurements
- Oil - Water primary imbibition centrifuge measurements

There are 47 samples with Multi-Speed Centrifuge (MSC) results and an equal number of MICP experiments used in the capillary pressure analysis. The procedure and conditions used in the experiments was discussed in Mookerjee, A. and Alias, A., (2006). The results were quality checked along the following steps:

1- Check that the gas permeability is higher than the water permeability, which is higher than the oil permeability at remaining water saturation, within a certain acceptable margin or errors. If it is not than the sample is classified as not suitable for use (36% of samples failed this criterion).

2- Check data for potential experimental errors in raw data, e.g. mechanical failures, scattered production data, lack of equilibrium at the end of each experimental step or abnormal trends. Results of those experiments may still be used but with caution.

3- Compare MICP with capillary pressures from centrifuge to check how severe is the latter affected by cleaning issues.

Out of the 47 samples, there are 14 samples that were either broken or fractured during the experiments and two samples were reported to have lost some grains during the experiments. These samples were excluded from the subsequent analysis. Mechanical errors (e.g. pump failure, measurement tool failure and power failure) were also considered during the analysis and modelling of the data. Some of the primary drainage experiment started with 90% saturation, as opposed to 100% saturation. These samples were given special attention in the subsequent analysis and modelling.

The production raw data in some samples was scattered or did not reach stability (no equilibrium) in some steps during the experiments, which raised concern about the analytical (Hassler and Brunner) results derived from these experiments. Samples which have these kinds of issues were not excluded immediately.

Comparison of MICP and Capillary Pressures from Centrifuge

All primary drainage curves from centrifuge measurements (Hassler and Brunner corrected) were compared to the equivalent MICP curves. It should be noted that MICP was measured on the trim ends of each plug. Due to inherent heterogeneity most of the trims do not have the same permeability as the whole plugs.

Proper plug cleaning is a critical precursor to representative experiments. Normally the plugs were cleaned between 1-3 months. The degree of cleaning is determined by the colour of the produced effluents. Furthermore, the salt content of methanol is checked by adding silver nitrate to the produced methanol. Despite following this procedure many of the measurements indicate cleaning issues. This manifests itself either in the entry pressure (centrifuge entry pressure is lower than that of MICP) and/or in the connate water saturation (centrifuge values higher than MICP values).

Normally MICP curves give lower estimate to connate water saturation than from curves derived from centrifuge experiments (corrected using Hassler and Brunner (1945) method). Uncertainty in MICP curves increases as saturation decreases (Meirose, J.C et al., (1993)). The mismatch between MICP and centrifuge analytical capillary pressure curves was handled as follows in the capillary pressure modelling: the MICP curves were used but modified to honour the connate water saturation from centrifuge capillary pressure curves and from saturation logs (method is described in steps in next section). The centrifuge capillary pressure curves provide a closer match to the connate water saturation from early logs saturation profiles (around 10%) than the MICP curves. However, using Hassler and Brunner corrected centrifuge curves (i.e. not simulated) will reduce the reliability of these curves around the end points.

CAPILLARY PRESSURE MODELLING

Capillary Pressure Model Used

After all of the drainage and imbibition capillary pressure were quality checked, they were modelled in order to be used in the field simulation models. The objectives of the capillary pressure modelling were:

1. To provide input into effective property modelling, which aims to investigate the impact of cm-scale heterogeneity on recovery.
2. To ultimately provide input into the dynamic modelling performed to define a new development plan for the field.

In the modelling step the experimental results are described by a set of equations. A set of parameters that have physical meaning are used to match the model to the experimental results. Once the model has been set-up it can be used to populate the simulation models with the appropriate capillary pressure curves. The model can also be used to derive imbibition curves from drainage curves (useful check on the consistency of the data).

In this exercise an improved Lambda capillary pressure model for carbonate reservoirs has been used. The equations for drainage and imbibition capillary pressures are:

$$P_c^{dra} = \frac{c_{wd}}{\left[\dfrac{S_w - S_{wc}}{1 - S_{wc}}\right]^{a_{wd}}} + \frac{c_{od}}{\left[\dfrac{1 - S_w - S_{or}}{1 - S_{or}}\right]^{a_{od}}} + b_d\left(S_{w\_cutoff}^{dra} - S_w\right) \qquad (1)$$

$$P_c^{imb} = \frac{c_{wi}}{\left[\dfrac{S_w - S_{wc}}{1 - S_{wc}}\right]^{a_{wi}}} + \frac{c_{oi}}{\left[\dfrac{1 - S_w - S_{or}}{1 - S_{or}}\right]^{a_{oi}}} + b_i\left(S_{w\_cutoff}^{imb} - S_w\right) \qquad (2)$$

where b_d is zero for water saturation higher than $S_{w\_cutoff}^{dra}$ and b_i is zero for water saturation less than $S_{w\_cutoff}^{imb}$ and c_{wd}, c_{od}, a_{wd}, a_{od}, b_d, c_{wi}, c_{oi}, a_{wi}, a_{oi} and b_i are fitting parameters used to fit experimental data. The formulae are an extension of the power-law form (equivalent to Lambda function) first introduced by Brooks and Corey (1966) (first term) and then extended by Skjaeveland et al. (1998) (second term) for mixed-wet reservoir rocks. Masalmeh, S. et al., (2006) introduce the third term to account for bioturbation. Given the type and appearance of data, the following fitting procedure was proposed initially which gives more physical meaning to the fitted curves.

- Drainage capillary pressure curves: focus on the first ‘water-wet’ term for the fit: a_{wd} to fit curvature, c_{wd} for entry pressure, other terms should be small (or zero)
- Imbibition capillary pressure curves: focus on the second ‘oil-wet term: a_{oi} to fit curvature, c_{oi} for entry pressure, other terms should be small (or zero)

This model is developed for less heterogeneous reservoirs than what this paper is addressing. Therefore, this procedure for fitting failed to provide an acceptable fit and one or more of the other terms were used as appropriate.

Application of the Capillary Pressure Model

The capillary pressure model described above has been applied to describe the experimental results. The underlying assumptions for the SCAL modelling exercise are:

- The entry pressure from MICP experiments and the connate water saturation from centrifuge experiments are honoured.
- Spontaneous imbibition for water is limited to a maximum of 2%. This low value is typical for carbonate rocks and consistent with the Amott and USBM indices measurements performed.
- All measured capillary pressure curves are bounding curves (those experiments that did not reach or start at connate water saturation were excluded and MICP curves were used instead).
- The available set of curves can be used to represent the full range of PRTs and permeabilities.

The steps in performing the capillary pressure modelling are:

1. Classify MICP and centrifuge capillary pressure curves by PRT.
2. Check curves and end points for trends (versus permeability bins and PRT ranges) but no obvious trends could be seen except a vague trend with permeability. Since no trends could be found in imbibition capillary pressure curves, a range was established for residual oil saturation of 3% to 17%.
3. For primary drainage curves, use the above described model and modelling approach to fit low and high curves for each PRT (upper/lower perm bound). However, using first term only made it very difficult to get the entry pressure and the second term parameters were used. Entry pressure honoured MICP and connate water honoured centrifuge. Figure 4 shows an example of one PRT curves fitted with low and high models. From this fitting exercise a correlation with permeability was only found for the connate water (equation (3)). The other parameters did not have correlation and some were fixed. The fixed parameters are: $a_{od} = 0.1$, $S_{w\_cutoff} = 1$ and $b_d = 0$.

$$S_{wc} = 0.137 \times k_g^{-0.1378}, \quad \text{for } k_g > 1 \text{ mD, for } k_g < 1 \text{ mD used } 0.15 \text{ mD} \tag{3}$$

4. Calculate the imbibition contact angle using MICP drainage curves as follows:
   a) Choose plugs with similar permeabilities and PRT (MICP and plug perms).
   b) Use method described in Masalmeh, S. and Jing, X. D., (2006) to calculate imbibition from drainage. This method requires three of the four main parameters to be known. The four parameters are: primary drainage capillary pressure curve, residual oil saturation, imbibition contact angle and imbibition capillary pressure curve. This method is only applicable for sample with negligible spontaneous imbibition.
   c) Vary the imbibition contact angle until a match to centrifuge curve is obtained (assuming drainage contact angle is zero as it don't have large impact with values up to 30^o (Masalmeh, S. and Jing, X. D., (2006))). Figure 5 shows two examples of plugs used in imbibition contact angle calculation (the sample has curves with all required parameters known except the contact angle). The average imbibition contact angle was found to be 125^o.
5. Calculate imbibition capillary pressure curves for all PRTs from drainage capillary pressure curves derived in step 3 assuming negligible spontaneous imbibition (Mookerjee, A. and Alias, A., (2006)) and an imbibition contact angle of 125^o. The residual oil saturation is assumed to be 0.1 for all PRTs and for both low and high ranges, since there was no correlation found between residual oil saturation values and permeability. When residual oil saturation was set floating in the modelling exercise, some inconsistent results found between different PRTs. The only unknown parameter of the four required parameters is the imbibition capillary pressure curve. Figure 6 shows an example of calculated curve for PRT C. This method is also used to calculate imbibition curves from MICP curves for PRT A, where imbibition centrifuge measurements are scanning curves i.e. did not start at

connate water saturation. The calculated imbibition curves in Figure 6 looks as if it is not matching the measured data points because of the two main assumptions on spontaneous imbibition and residual oil saturation.

6. The calculated imbibition capillary pressure curves (step 5) are fitted with equation (2) for simplicity (so the parameters could easily be used in the later dynamic modelling process). The following fitting was performed:
    a. Fit the calculated imbibition curves using equation (2) and aim to fix the 1st term parameters to low values (0.3) and vary the second term.
    b. Check if parameters have a relationship with permeability so that they can be parameterised or if they can be fixed. Generally the coefficients could not be parameterised. However, some could be fixed. The fixed parameters are: S_{or}=0.1, c_{wi} = a_{wi} = 0.3, a_{oi} = 0.7 and b_i = 0. Table 1 shows an example of the fitting coefficients for PRT A, B, C, D and E.

Impact on Reservoir Performance and Uncertainty

The fine scale heterogeneity has high impact on conformance of water flooded layers. Figure 2 shows an enlargement of a 20 cm core which is taken from water flood layer. This core shows difference in oil staining and there is more oil saturation in the tighter parts. Assigning different dynamic properties to each PRT can explain part of the fact that current recovery of this field is around 20 % despite that it was produced for 40 years.

Detailed conceptual water-oil models showed that recovery from homogeneous (averaged properties) is higher than from the detailed PRT models. Some principal rock types have high entry pressure and hence it requires large pressure drop to get high recovery from water flood and in such heterogamous fractured reservoir it is very difficult to get. So the new model gives a better description of the reservoir behaviours and the new SCAL measurements reduced some uncertainties such as spontaneous imbibition reduced from 15% to 2% and residual oil saturation range changed from (0.1 – 0.4) to (0.03 – 0.17). This new understanding of the capillary pressure led to a conclusion that waterflood is not the best option and hence steam is considered and being studied.

CONCLUSIONS

- The product of the rigorous screening procedure helped in filtering the suspected data and provides good confidence in the subsequent capillary pressure modelling work.
- The modified lambda equation as proposed by Masalmeh can be applied to this dataset to get a reasonable uncertainty range of capillary pressure model for each PRT grouping.
- A reasonable correlation with permeability was found for connate water saturation and no correlation found for residual oil saturation.
- The imbibition curves were successfully calculated from drainage curves as proposed by Masalmeh (Figure 5). Using a realistic imbibition contact angle of 125

degrees an acceptable imbibition model could be achieved for imbibition capillary pressure curves (Figure 6).

- Understanding capillary pressure curves helped to explain part of the low recovery values seen in the heterogeneous field.
- Capillary pressure curves and conceptual models assisted in getting the correct dynamic water flood performance.

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REFERENCES

Brooks, R.H. and Corey, A.T: “Properties of Porous Media Affecting Fluid Flow”, J. of the Irrigation and Drainage Division, Proc. of ASCE, 92, No. IR2, (1966) 61-88.

Creusen, A., Maamari, K., Tull, S., Vahrenkamp, V., Mookerjee, A., Van Rijen, M: “Property Modelling Small Scale Heterogeneity of Carbonate Facies”, SPE 111451, SPE/EAG Reservoir Characterization and Simulation Conference, Abu Dhabi, U.A.E., (2007).

Hassler. G.L. and Brunner. E: “Measurement of Capillary Pressure in Small Core Samples”. Trans. AIME (1945) 160. 114-123.

Masalmeh, S.K. and Jing, X.D: “Capillary Pressure Characteristics of Carbonate Reservoirs: Relationship between Drainage and Imbibition Curves”, SCA 0616, Presented at the SCA conference, Trondheim, Norway, (2006).

Masalmeh, S.K., Abu Shiekah, I. and Jing, X.D: “Improved Characterization and Modeling of Capillary Transition Zones in Carbonate Reservoirs”, SPE 109094, Presented at the 2005 International Petroleum Technology Conference, Doha, Qatar, (2006).

Meirose, J.C., Dixon, J.R. and Mallinson, J.E: “Comparison of Different Techniques for Obtaining Capillary Pressure Data in the Low-Saturation Region”, SPE 22690, presented at the 1991 SPE Annual Technical Conference and Exhibition, Dallas, USA, October 6-9, (1993).

Mookerjee, A., Alias, Z: “Core Analysis Program For A Giant, Complex Fractured Carbonate Field in Oman: Learnings and Key Results”, SCA 0619, Presented at the SCA conference, Trondheim, Norway, (2006).

Skjaeveland, S.M., Siqveland, L.M., Kjosavik, A., Hammervold, W.L., Virnovsky, G.A: “Capillary Pressure Correlation for Mixed-Wet Reservoirs”, SPE 39497, paper presented at the SPE India Oil and Gas Conference and Exhibition, New Delhi, India, February 17-19, (1998).

Vahrenkamp, V. C., Creusen, A., Tull, S., Farmer, A., Mookerjee, A., and Al Bahry, A: “Multi-scale heterogeneity modelling in a giant carbonate field, northern Oman” GEO 118947, presented at Geo 2008 in Manama, Bahrain, (2008).

Table 1. Summary tables of coefficients from equations (1) and (2) used in modelling WO capillary pressure measurements. The other parameters are constant (a_{od} = 0.1, S_{w_cutoff} = 1, b_d = 0, c_{wi} = a_{wi} = 0.3, a_{oi} = 0.7 and b_i = 0).

PRT A	
Swc	0.15
Sor	0.10
c_{wd}	79.09
a_{wd}	0.40
c_{od}	-32.64
c_{oi}	-19.03

PRT B	
Swc	0.07
Sor	0.10
c_{wd}	13.50
a_{wd}	0.40
c_{od}	-7.30
c_{oi}	-3.39

PRT C	
Swc	0.11
Sor	0.10
c_{wd}	19.50
a_{wd}	0.40
c_{od}	-10.00
c_{oi}	-5.10

PRT D	
Swc	0.13
Sor	0.10
c_{wd}	17.43
a_{wd}	0.40
c_{od}	-7.50
c_{oi}	-4.53

PRT E	
Swc	0.03
Sor	0.10
c_{wd}	3.71
a_{wd}	0.40
c_{od}	-2.50
c_{oi}	-1.40

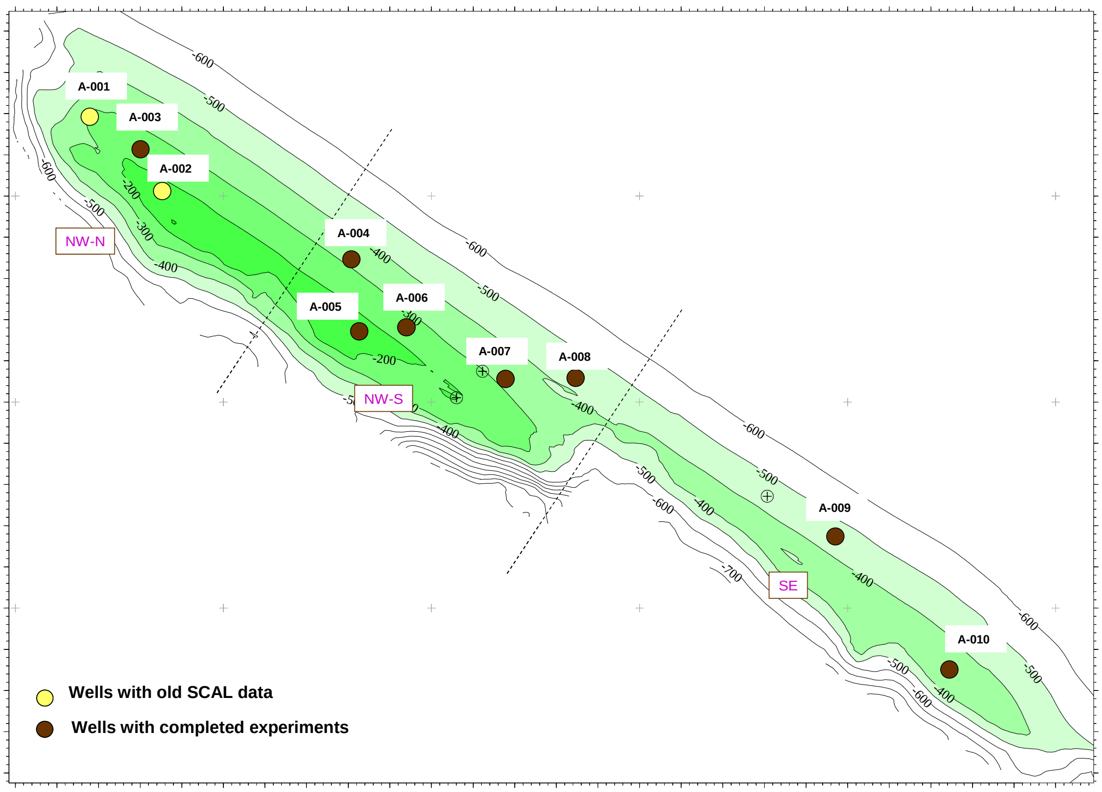

Figure 1. Overview of the field and location of the recent cored wells

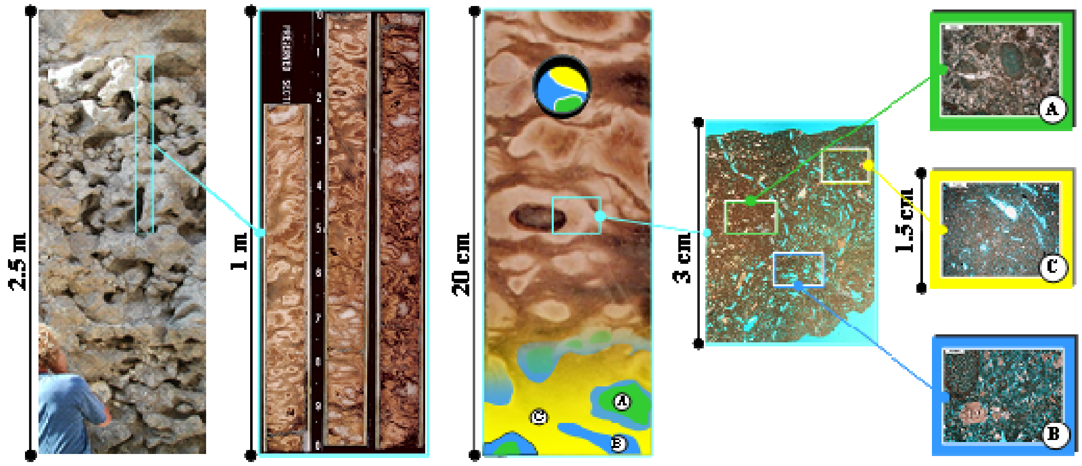

Figure 2. Evolution of PRTs from outcrop to core to thin section scales.

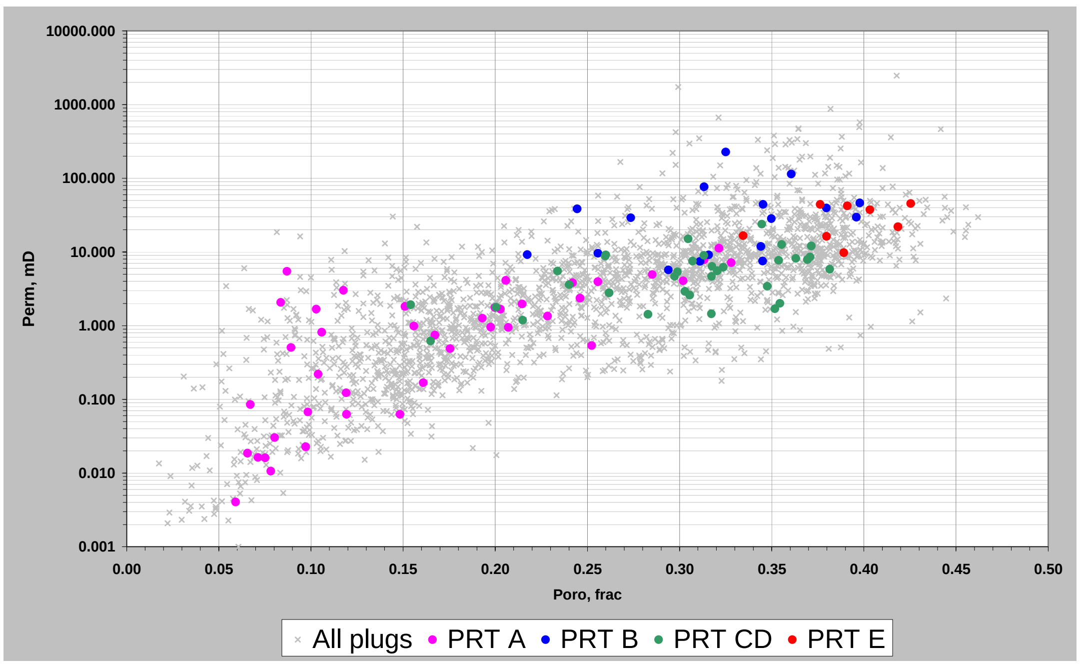

Figure 3. Poro-perm distribution indicating PRT classification. The grey points indicate all available measurements and coloured points indicate samples that have PRT classification.

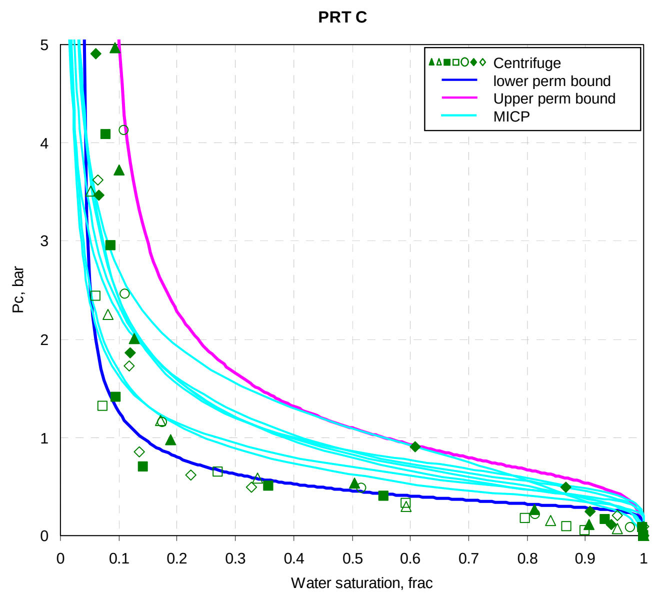

Figure 4. Drainage capillary pressure curves (centrifuge and MICP) fitted with low and high models for PRT C.

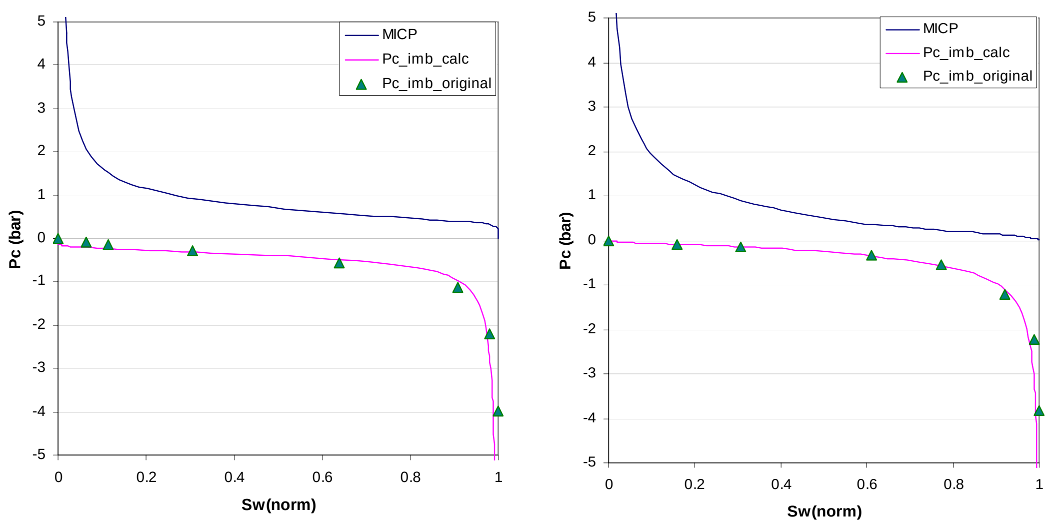

Figure 5. Two examples of plugs used for contact angle calculation. Blue line is the MICP curve, green marks are normalised imbibition capillary pressure curves from centrifuge and red is calculated curve from MICP drainage to get the contact angle.

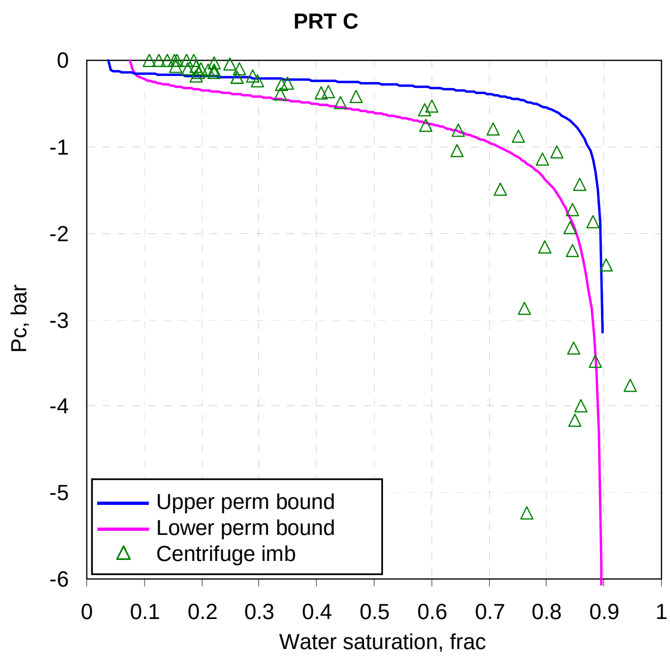

Figure 6. Imbibition capillary pressure curves. The marked curves are centrifuge measurements and blue and red are the calculated (from drainage using a contact angle of 125^o) high and low curves respectively.