# State-of-the-art SCAL experiments and interpretation

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## Abstract

An understanding of the imbibition-relative permeability of hydrocarbons and water is essential for reservoir simulation. The remaining hydrocarbon saturation after water flood (and hence the ultimate recovery) is strongly determined by the tail-end shape of the imbibition-relative permeability curve, close to the residual hydrocarbon saturation.

Interpretations of SCAL data sets are presented which highlight the importance of restoring wettability to core plugs prior to analysis. A very large reduction is seen in residual oil saturations for the particular reservoirs.

Numerical simulations are then used to history match the raw experimental production data. The process corrects for experimental artefacts and experimental limitations, and results in a significant reduction in residual hydrocarbon saturations compared to typical analytical interpretations.

## Introduction

The Maui BD oil sands (Figure 1) have been producing since October 1996 via the FPSO Whakaaropai. The reservoirs have an expectation STOIIP of 12.1 million m$^3$. Work on residual gas measurements (Adams et al., 2000) in the overlying Maui C gas/condensate sands in 1997 was the catalyst for the work presented in this paper.

The existing (pre-1998) oil relative permeability data used in the Maui BD oil sands were based on centrifuge measurements in the deeper BF oil sands for Corey exponents, and centrifuge BD sand measurements for endpoints. These experiments were carried out at room temperature with mineral oil on cleaned samples, and the data interpreted with analytical techniques. The collated data resulted in residual oil saturations of 30-35% and Corey exponents of 2. The

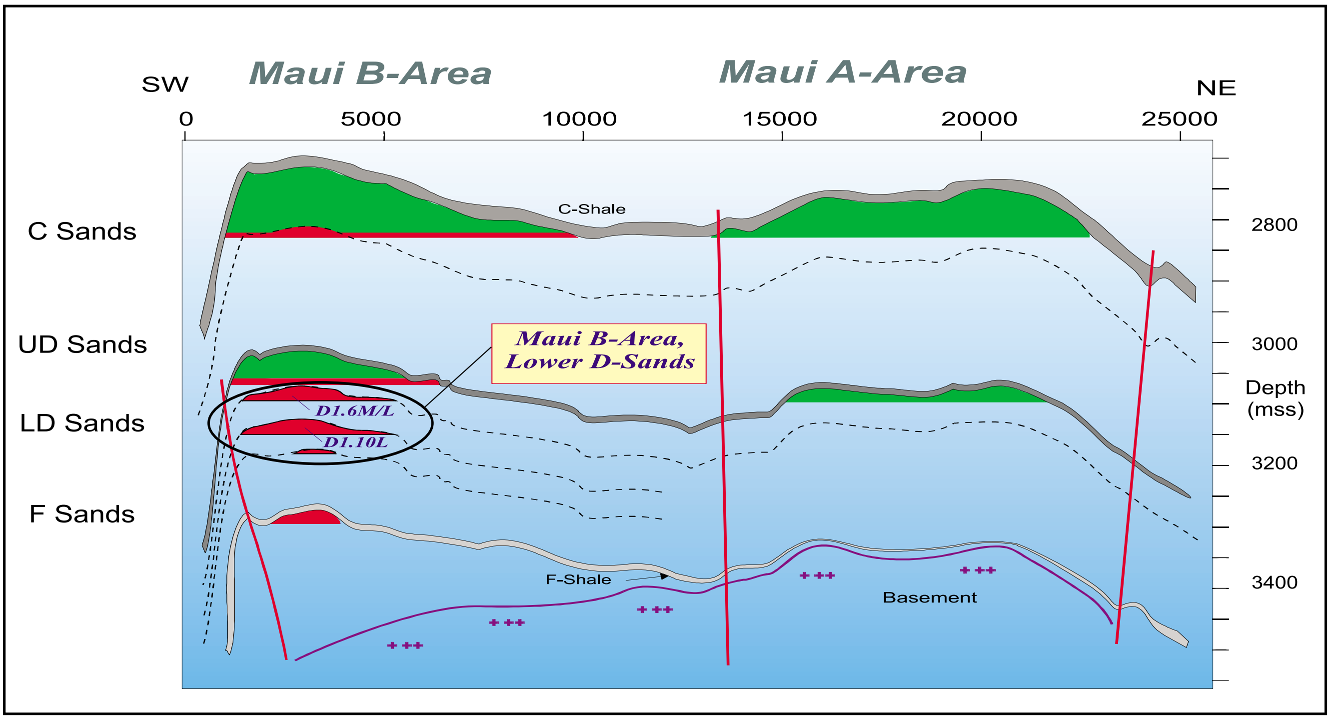

Figure 1: Maui BD oil sands.

Corey exponents derived from the D sand core plugs were rejected as they gave Corey exponents of 7 to 8.

These residual oil saturations are high compared with recent state-of-the-art special core analysis (SCAL) studies carried out on sandstone reservoirs from various fields around the world (Kokkedee et al, 1996). In these studies, a systematic reduction in residual oil saturations, in combination with higher Corey exponents, were observed.

There are two reasons that could explain the likely too-high estimates for earlier $S_{or}$ data.

The measurements were performed on core material that was left water-wet after cleaning. The cleaning methods employed on the BD core plugs are believed to be questionable and might be the cause of the very high Corey exponents observed (7-8) and possibly account for the high $S_{or}$ values. It is likely that the existing data is not representative of the reservoir. Asphaltenes are present in the Maui crude and can have a large impact on wettability (Anderson, 1987).

The experimental data were interpreted using conventional analytical methods in which, by definition, it is assumed that the capillary pressure is negligible. Recent Shell research has shown that the underestimation of capillary end-effects in the analytical interpretation methods may lead to $S_{or}$ values that are 10-15% too high (Kokkedee et al., 1996).

This paper documents the results of an extensive special core analysis program carried out in 1998, for the Maui BD sands, to investigate these issues.

# Experimental program

The basic SCAL program was outlined as follows:

- acquire sufficient measurements to ensure representative coverage (facies, porosity, permeability);
- determine impact of ageing on residual oil saturation and (oil, water) relative permeability;
- measure drainage and imbibition capillary pressure curves for use in simulation of the relative permeability raw data; and
- quantify repeatability of the experiments.

To restore wettability to the cleaned water-wet core samples, all plugs were batch aged in an oven at appropriate reservoir temperature and pressure. Two spare samples were set up with all the SCAL samples and permeability to oil measured every few days. The permeability to oil stabilised after approximately 24 days, indicating wettability had been restored.

Measurements were made using the centrifuge and steady-state techniques. Details of these methods have already been published and will not be repeated here (Hassler et al, 1945; Hagoort, 1980), but a summary is presented below.

## Steady-state experiment

In the steady-state technique, two immiscible fluids are injected simultaneously at constant rates into a core plug at a given fractional flow ratio. Measurements are made at each fractional flow until steady-state conditions are reached. A number of different fractional flows are used from 100% oil to 100% water flow. Pressure drop, saturation and flow rates are monitored. Relative permeabilities can then be calculated using Darcy's law.

The technique cannot determine residual saturations with high precision within a reasonable measurement time because of the low relative permeabilities when approaching residual saturations. Estimates of $S_{or}$ made using the steady-state technique are considered to be maximum values.

## Centrifuge experiment

During a centrifuge experiment, a core plug is saturated with one phase and spun round, at a fixed centrifugal acceleration, in a core holder filled with the other phase. The production of the one phase, expelled from the core plug by the centrifugal force, is measured as a function of time. In an imbibition experiment, oil is expelled from the plug and the oil relative permeability $k_{ro}$ can be determined for decreasing oil saturation. In a drainage experiment, water is expelled and the water relative permeability $k_{rw}$ can be determined for decreasing water saturation.

Multi-speed centrifuge experiments are carried out at series of fixed centrifugal accelerations and are used to determine capillary pressure. Also relative permeability of the expelled phase can in principle be determined from a multi-speed experiment.

### Water-oil $P_c$ (by centrifuge)

Fourteen samples were measured with the centrifuge (multi-speed). All samples were aged (i.e. the imbibition and secondary drainage cycles were carried out after ageing). These curves offer an independent estimation of residual oil saturation after the imbibition cycle. The full curves were used as input in numerical simulation of the relative permeability data.

### Water-oil relative permeability (by centrifuge)

Fourteen samples were measured with the centrifuge (single-speed), all samples being aged. After ageing, the imbibition and second drainage cycles were run to determine $k_{ro}$ and $k_{rw}$ curves. This data is the most accurate for residual saturation determination.

### Water-oil relative permeability (by steady-state)

Three samples were measured with the steady-state apparatus. The mid-saturation range of the relative permeability curve can be inaccurately estimated from centrifuge experiments if interpreted analytically and steady-state experiments are recommended for this saturation range. Numerical interpretation of the centrifuge experiments should be able to largely remove the inaccuracy in the mid-saturation range. Another objective of the steady-state experiments therefore is to confirm the numerically interpreted centrifuge experiment values for this range. The steady-state experiments are time-consuming and expensive, so only three plugs were chosen. These measurements should not be used when determining saturation end-points.

## Quality control

### Dean-stark checks

A comparison was made between the residual values reported for the last cycle on each experiment, and the saturations measured using Dean-Stark extraction. On average the difference was 2 - 3%, although some plugs exhibited 5 - 10% difference. This information was considered when determining the final residual oil and Corey exponent values.

### Bond number

De-saturation effects can cause changes in capillary pressure and relative permeability at high flowrate and/or low interfacial tension, which (usually) do not occur under normal field conditions. To avoid these effects, the critical Bond number (ratio between gravitational and capillary forces) should not exceed the value of $10^{-5}$ (Shell estimate). This Bond number requirement implies an upper limit for the centrifugal acceleration. The experiments carried out at a Bond number much higher than $10^{-5}$ were discarded.

### Repeatability

Seven samples were re-run to check the experimental repeatability. The majority of samples repeated well. Repeat experiments typically showed a maximum difference in residual oil saturation of about 3%.

## Analytical interpretation

The analytical interpretation of the raw data is an established technique (Hassler and Brunner, 1945; Hagoort, 1980) and will not be presented here.

A comparison of the 1998 vs pre 1998 residual oil measurements is shown graphically in Figure 2 along with an average of both sets of data. There is a large reduction in residual oil saturation (about 17%) that can be attributed to the 1998 dataset being aged. This clearly shows the critical importance of core analysis being made on representative (i.e. aged) core plugs.

## Numerical interpretation

The centrifuge technique is a relatively fast technique, which provides information on capillary pressure or relative permeability (for expelled phase only). It is impossible to fully separate the two rock properties in practise and numerical simulation is the appropriate tool to unravel the separate role of capillary pressure and relative permeability in the centrifuge data. In addition, a number of experimental factors influence the data as well.

A finite mobility of the invading phase affects early production in particular and results in errors in the analytically derived relative permeability at high saturations of the expelled phase. With numerical interpretation this error is avoided. Another experimental factor is the start-up time of the centrifuge, which causes a delay in production and thus also results in an error in the analytically derived relative permeability at high saturations of the expelled phase. This start-up effect is also corrected for by numerical interpretation.

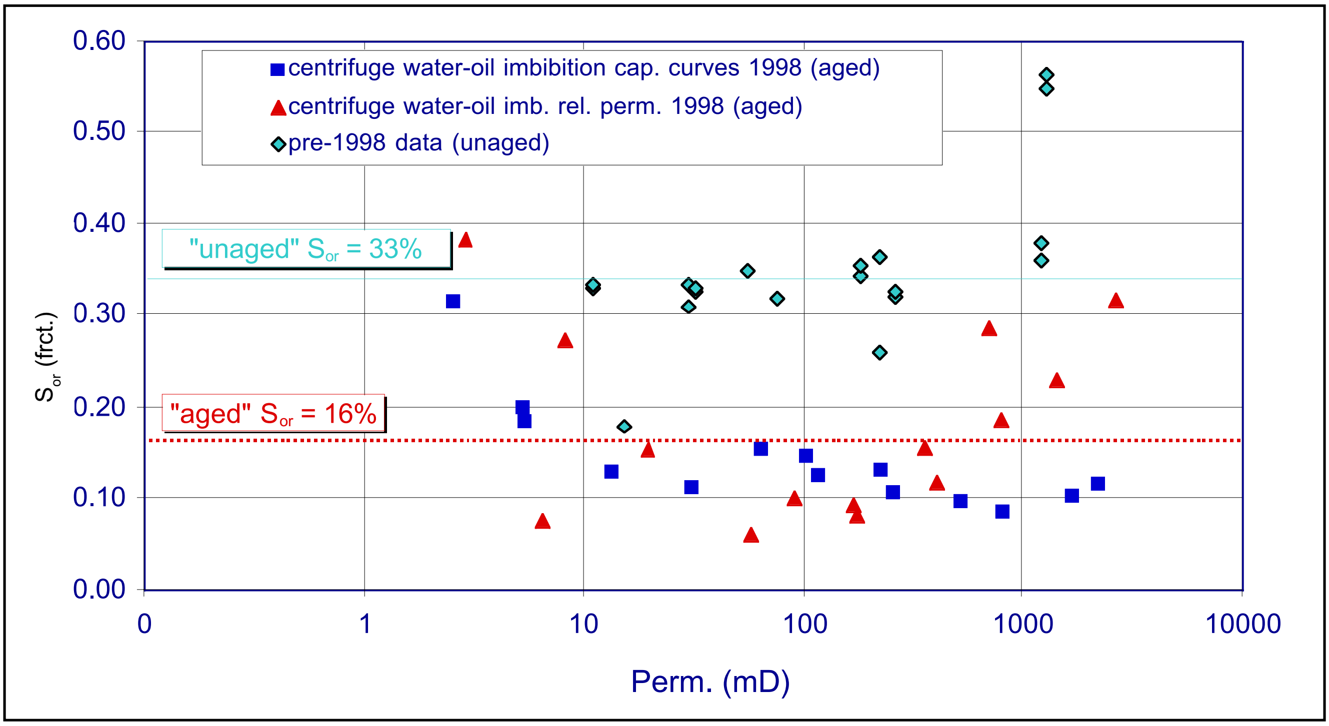

Figure 2: Analytically interpreted residual oil saturations – comparison between pre-1998 data (unaged) and 1998 data (aged)

Yet another experimental factor that can only be corrected for by numerical interpretation, is a non-constant centrifugal acceleration along the sample.

## Interpretation

The MoReS (Shell proprietary) reservoir simulator (Regtien et al., 1995) has been used to determine relative permeability from raw production data by history matching the simulation to the experimental data. Capillary pressure curves used were derived from a relationship between porosity and measured water-oil $P_c$ data.

A typical example of a SCAL interpretation by numerical interpretation is given in Figures 3 and 4. In Figure 3 the match on the measured average saturation in the sample as a function of time is shown. Figure 4 shows the saturation distribution in the sample at the end of the experiment, illustrating a large capillary hold-up effect, which would introduce a significant error if the experiment was interpreted analytically instead of numerically.

In the fitting process, the Corey exponents of both phases and the residual saturation have been allowed to vary within realistic limits. The end-point relative permeabilities have been kept fixed at the measured values whenever possible. Only when a reasonable match could not be obtained were these end-point values allowed to vary.

## Numerical results

Note that all results presented are referenced to laboratory conditions. Before applying the results to reservoir simulation models, the data has to be corrected to in-situ conditions.

Figure 5 shows a typical example of the resulting relative permeabilities for an oil/water imbibition experiment (same as in Figures 3 and 4) as interpreted analytically by the contractor (CoreLabs), as interpreted analytically with the Hagoort method (Hagoort, 1980) and as interpreted numerically. The two analytical methods agree very well in general, except for the end-point relative permeability (in the contractor's analytical method, the end-point has been shifted to the measured value).

The imbibition fits are in general of a better quality than the 2nd drainage fits. For all 2nd drainage experiments the end-point relative permeability value had to be varied, whereas only a selection of the imbibition experiments had to have end-points varied.

## Steady-state interpretation

Figures 6 and 7 compare the steady-state and (numerically interpreted) centrifuge-relative permeabilities for imbibition and 2nd drainage respectively. Figure 6 shows a good agreement between the two measurement techniques, thus

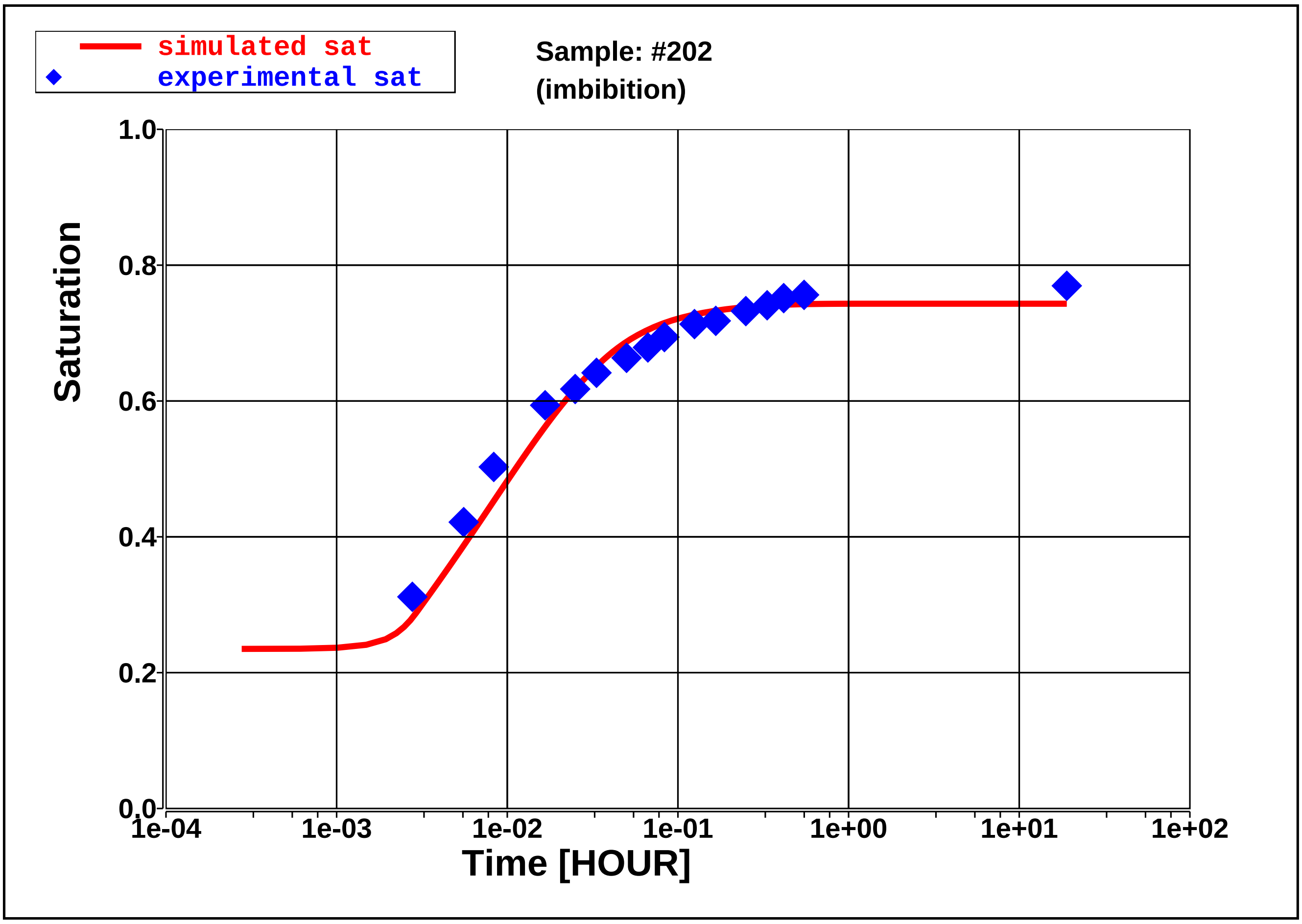

Figure 3: Typical example of history match on measured average saturation in sample.

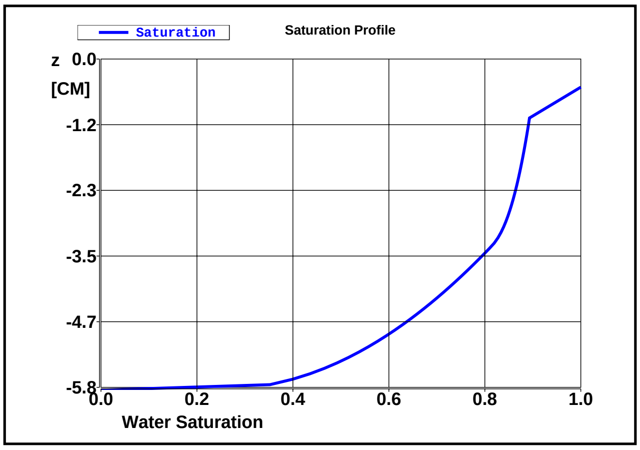

Figure 4: Typical example of simulated saturation distribution in sample at end of experiment

illustrating that numerical interpretation of the centrifuge experiments properly corrects for experimental errors in the mid-saturation range in case of oil/water imbibition.

As shown in Figure 7, the agreement between the two SCAL techniques for 2nd drainage is not as good as for the imbibition experiments. This may be partly due to spontaneous drainage effects. However, the 2nd drainage data are only used to determine the average water Corey exponent and the shapes of the steady-state and centrifuge curves are in reasonable agreement, so numerical interpretation of the centrifuge experiments is a sufficient correction also for 2nd drainage.

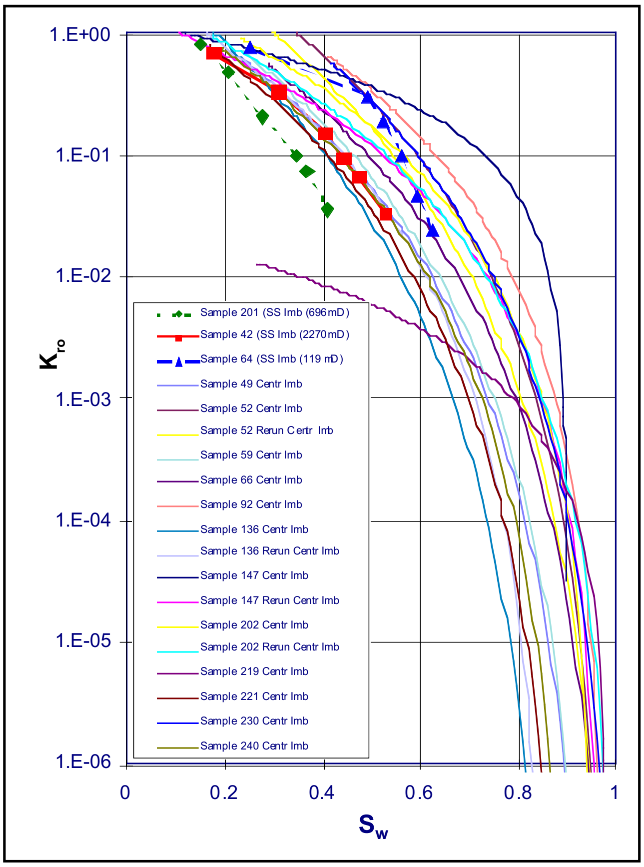

Figure 6: Oil-relative permeability (imbibition) from centrifuge and steady-state measurements (steady-state with markers).

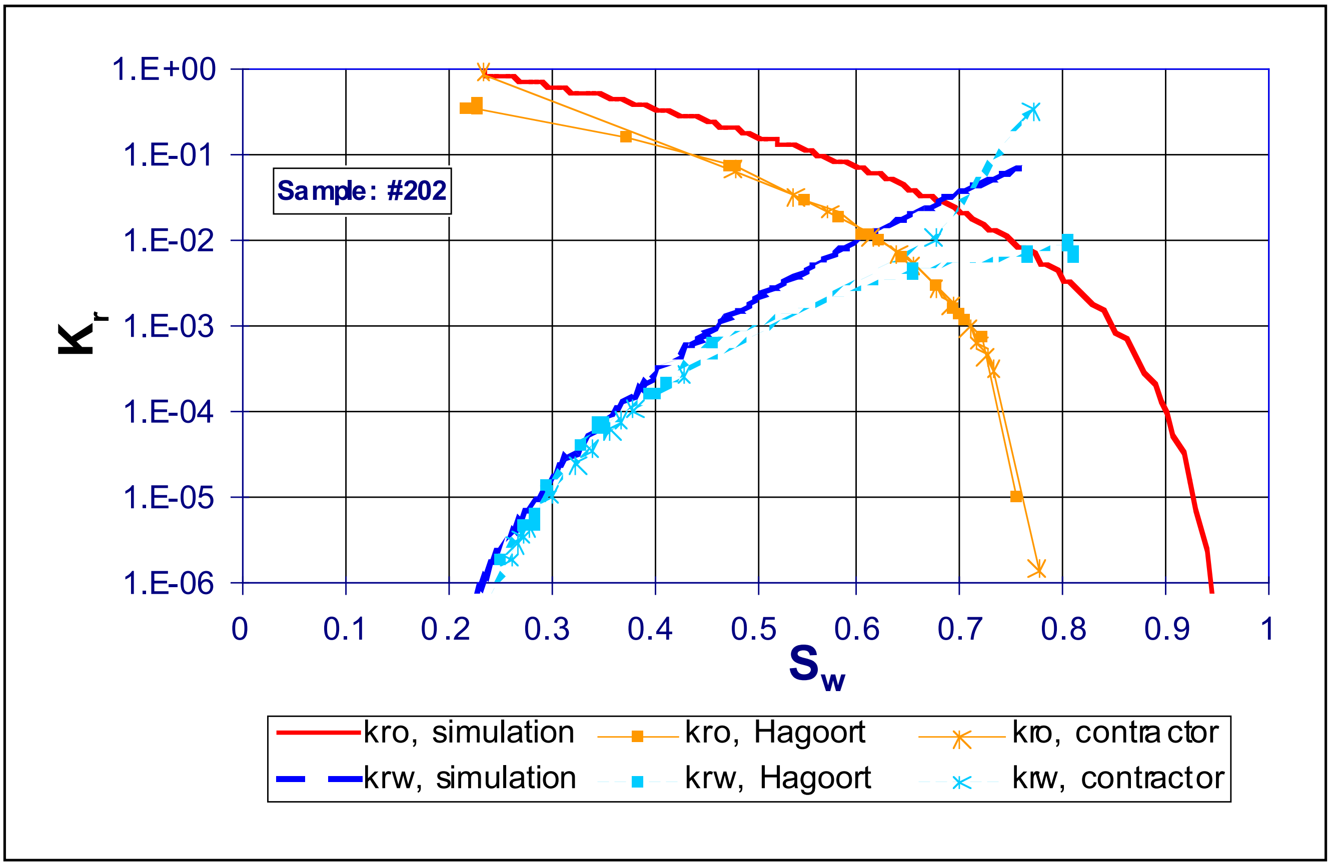

Figure 5: Typical example of oil/water imbibition relative permeabilities as derived analytically and by numerical simulation.

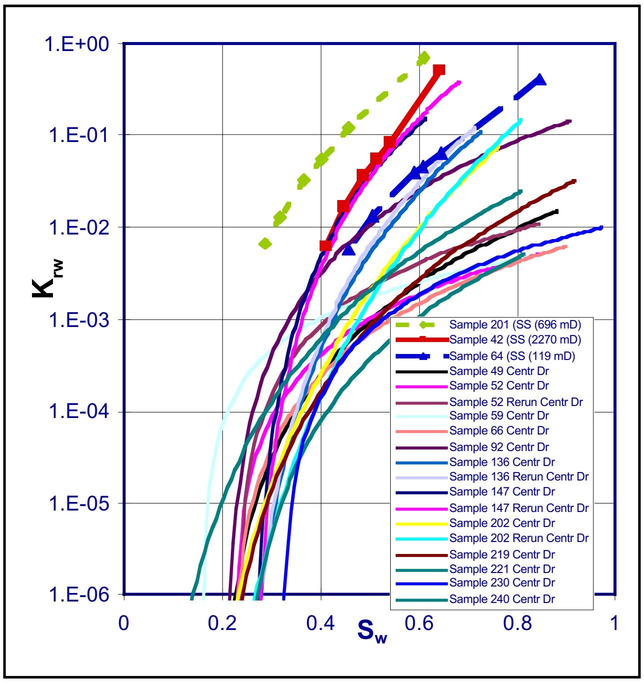

Figure 7: Water-relative permeability (2nd drainage) from centrifuge and steady-state measurements (steady-state with markers).

The steady-state data was not used in averaging residual saturations.

## Results

Analytical interpretation resulted in an average residual oil saturation (imbibition experiments) of 16%. Numerical interpretation results in an average of 11%. (This comparison is made at an oil relative permeability value of $10^{-5}$).

Figure 8 compares the analytically and numerically interpreted residual oil saturations from the relative permeability centrifuge experiments. The various reservoir units within the Maui BD oil sands show no distinct behaviour. Noted on this figure are the numerically simulated samples that had a poor history match.

In Figure 9 the ("good") simulation results are plotted with the residual oil saturations derived from the capillary pressure forced imbibition cycle. Highlighted are the data points that were excluded from either the low, base or high $S_{or}$ regressions. For these regressions a Land correlation (Land, 1968) between $S_{or}$ and connate water saturation has been used.

In the averaging of the results, the dubious results have been left out, i.e. the experiments with poor agreement with Dean-Stark values, the experiments with a poor history match and the experiments with a too high Bond number. No pre-1998 data has been used.

For input into reservoir simulation of the Maui BD oil sands all parameters have been taken from the imbibition experiments except for the Corey exponent for water, which was taken from the (more realistic value of the) 2nd drainage experiments.

## Conclusions

Analytical interpretation of the new data shows a significant decrease in the most likely value of residual oil saturation to 16% (compared with an average of 33% obtained previously on water-wet plugs). Numerical simulation of the experiments has further reduced the average residual oil saturation to 11%.

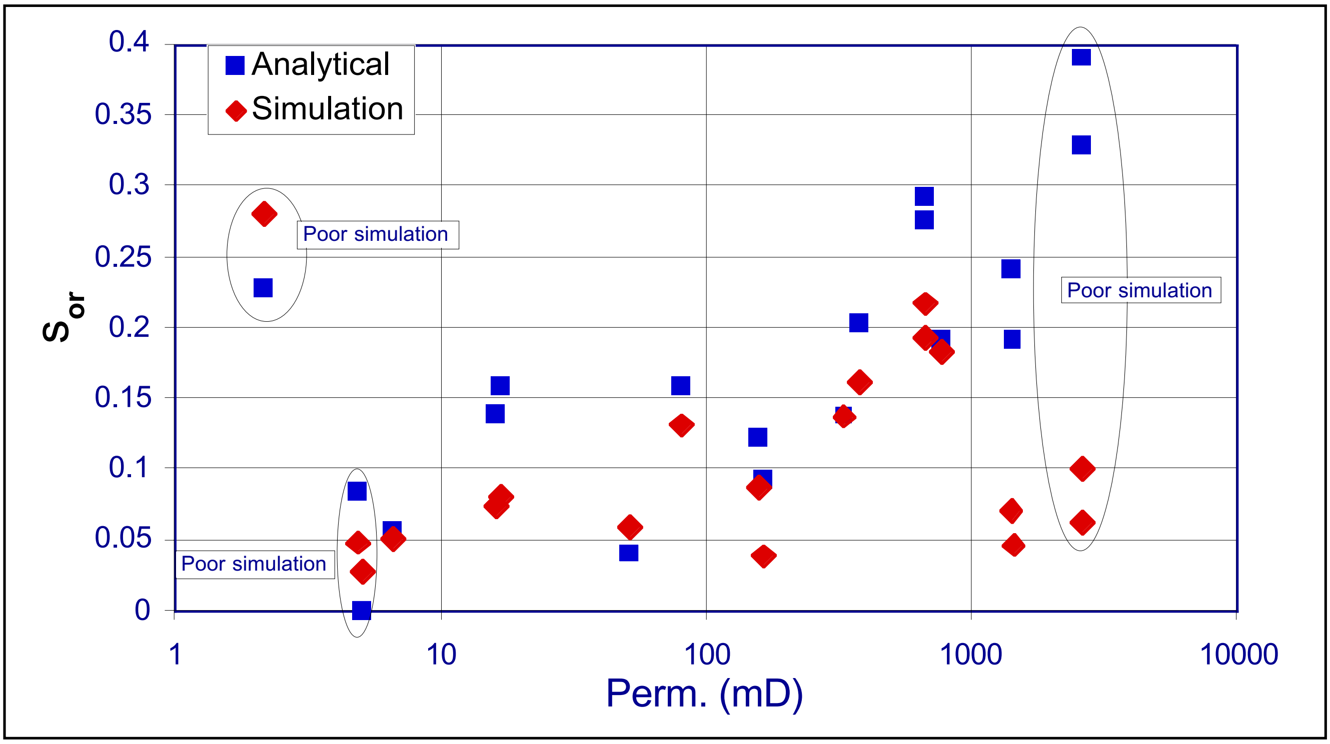

Figure 8: Comparison of numerically and analytically interpreted residual oil saturations.

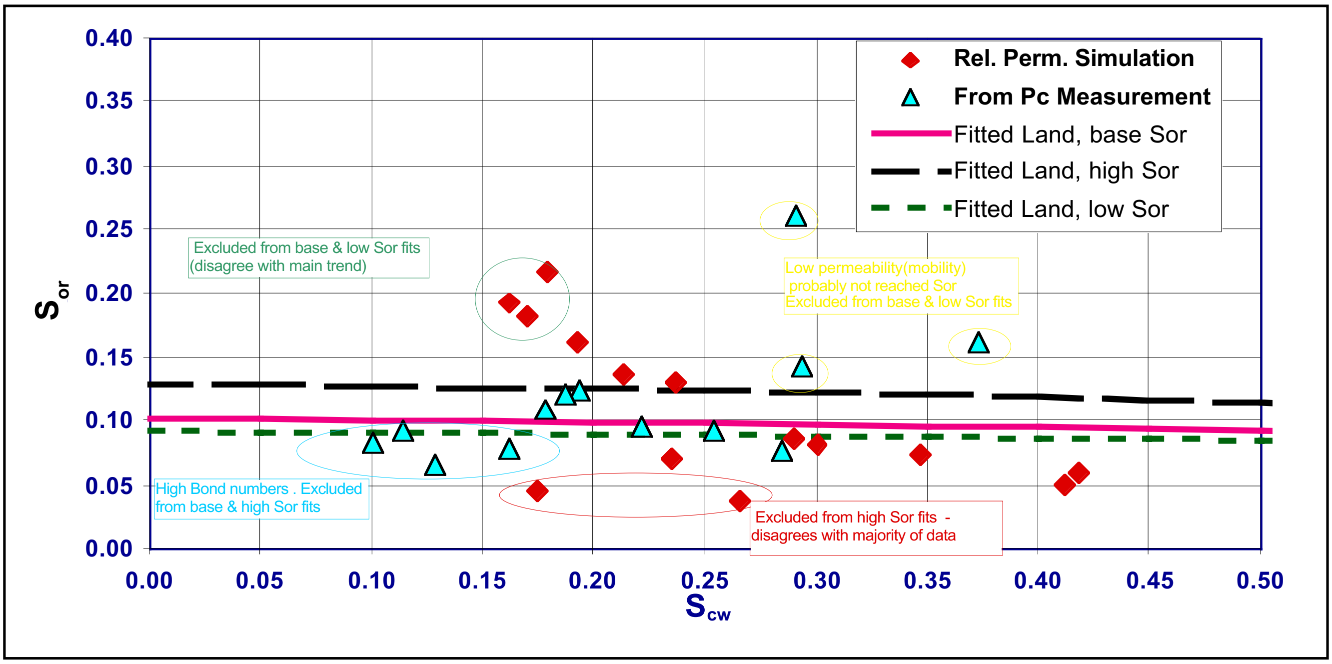

Figure 9: Residual oil saturation (imbibition) from relative permeability and capillary pressure curve measurements.

Corey exponents of $n_o = 2$ and $n_w = 2$ were previously used in the BD oil sands for oil/water imbibition as derived from BF oil sands data. Numerical simulation of the 1998 experiments results in values of $n_o = 4.6$ and $n_w = 2.9$, which can be attributed to the 1998 measurements being made on restored-wettability plugs.

Oil-water relative permeability curves, and associated residual oil saturation values are substantially affected by the wettability of the core plug. All future core analysis for the Maui oil reservoirs must be carried out on plugs that are aged at reservoir temperature and pressure for up to four weeks. Numerical simulation of core experiments is critical in determining accurate residual saturations and Corey exponents.

Use of lower residual oil saturations together with the appropriate relative permeabilities in reservoir simulation has significantly improved the history match in both the Maui BD and BF oil sands, where the latest BD SCAL results were also implemented.

It has also resulted in increased reserves in the Lower BD sands and the BF sands. Application of this state-of-the-art SCAL technology to other oil fields where recovery is driven by water sweep is likely to have a similar impact.

## Nomenclature

$k_{ro}$ oil-relative permeability [-]

$k_{rw}$ water-relative permeability [-]

$n_o$ oil Corey exponent [-]

$n_w$ water Corey exponent [-]

$P_c$ capillary pressure [Pa]

$S_{or}$ residual oil saturation [-]

$S_w$ water saturation [-]

$S_{wirr}$ irreducible (connate) water saturation [-]

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