Laboratory and in-situ determination of residual gas saturations in Maui

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Abstract

A review has been undertaken of the residual gas saturations in the main producing sands of the Maui Gas Field. Additional laboratory data has been acquired and interpreted to address recognised deficiencies in the existing dataset. Residual gas saturation in the Maui Field has been shown to be dependent on the initial gas saturation in the individual rock sample. Relationships representing the high, expectation and low case residual gas saturations have been derived from the laboratory results and checked against field measurements using pulsed neutron logs. The work described herein supports a decrease in the most likely value of the residual gas saturations and, as a direct consequence, the remaining reserves of the Maui Field have increased significantly.

Introduction

Laboratory analyses carried out in 1996 indicated residual hydrocarbon saturations in the Maui Field may be significantly lower then the 30% then carried in reservoir simulation models. The work reported here details investigations carried out in 1997 for the main gas reservoir — the Maui C sands — to determine most likely residual gas saturations.

The investigation was carried out on three fronts:

- a literature search for quantitative data from analogous fields;
- laboratory analyses designed and carried out on representative samples; and
- in-situ measurements of residual gas saturations using pulsed neutron logs.

The importance of residual gas

Petroleum engineers spend a significant amount of time attempting to quantify the reserves of hydrocarbon accumulations, since these volumes control sales and the financial investment required to produce the sales volumes.

In a water-drive reservoir such as Maui, the residual gas saturation is important to know because it provides an indication of how much gas will be left behind once water has swept through a unit. The difference between how much gas was originally present and the volume of gas left behind is the producible gas volume, or reserves. Reservoir simulation of Maui attempts to model this water sweep along with produced gas volumes in order to estimate the remaining gas reserves. Hence, a reduction in residual gas saturations expected for a model will yield an increase in the producible gas volumes estimated.

Residual gas prior to 1997

At the start of 1996, the residual gas saturations (Sgr) in the Maui Field were based on a plot of residual gas saturation against porosity (Figure 1). Note that data considered unrepresentative owing to experimental failure or sample damage has been excluded. The remaining data shows no discernible pattern of variation with porosity. The measurements range from a high of 36% to a low of 26% of pore volume, suggesting the uncertainty in any average is high. It is noteworthy that there is no apparent difference between the experimental techniques used. From the plot, an average residual gas saturation of 30% was selected for all reservoir.

To improve the quality of Sgr data, some end-point air-brine centrifuge measurements were made during 1996. The data acquired are displayed in Figure 2a along with the earlier residual gas saturation data. The data suggest that Sgr values lower than the average of 30% are appropriate. Moreover, a relationship linking lower Sgr values to lower porosities is suggested.

Literature investigation suggests that a relationship between initial (irreducible) water saturation and residual gas saturation is more likely than one based on porosity (Firoozabadi et al. 1987, Land 1968, Torsaeter 1984). Figure 2b shows the data in such a form. Although linear relationships are shown, there is no reason to assume that

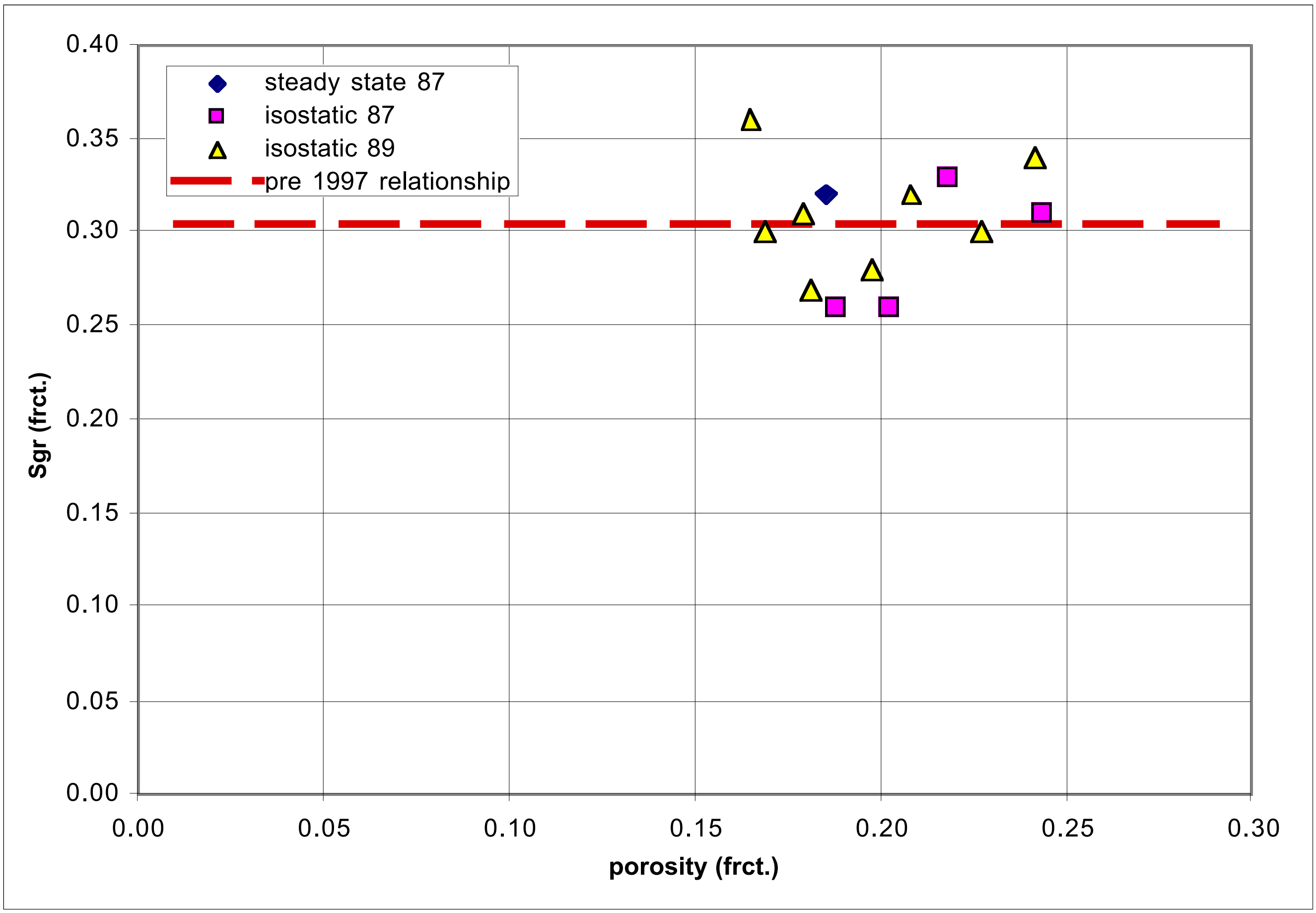

Figure 1: Plot of porosity against laboratory derived residual gas saturation (Sgr). Data has been acquired using the laboratory techniques denoted during the years given.

these relationships should be linear. Indeed, it is later shown that a curved relationship better describes the data.

In Figure 2b the discrepancy between the older data and the 1996 measurements is readily apparent. The more recent data shows significantly lower residual gas saturations. The three 1996 points apparent at higher Sgr values are from damaged (fractured or cracked) plugs. When these plugs are ignored, a relationship between initial (irreducible) water saturation and residual gas saturation is discernible. A variation in residual gas saturation associated with reservoir quality is apparent.

At this stage, it was decided that further investigation was necessary to resolve the differences between the new and the old data. Two routes were selected:

- additional core analyses; and
- looking for residual gas saturations in the field.

Core analyses

Before proceeding with any additional core analyses, it was important to understand what measurements had already been acquired and why they should be different. It was also necessary to consider in detail what might be happening in the reservoir and how this could best be modelled in the laboratory.

The residual gas saturations used to develop the pre-1996 Maui reservoir model came from two different experimental techniques: the steady-state and the unsteady-state (isostatic) experiments.

Steady-state

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% brine flow. Pressure drop, saturation and flow rates are monitored.

The technique cannot determine residual hydrocarbon saturations with high precision within a reasonable measurement time because of the low relative permeabilities when approaching residual hydrocarbon saturations. In addition the large mobility contrast between gas and water requires extreme fractional flows which are difficult to achieve. Estimates of Sgr made using the steady-state technique are considered to be maximum values.

Unsteady-state

The unsteady-state method involves brine displacing oil from initial water saturation. A core plug in a holder is 100%

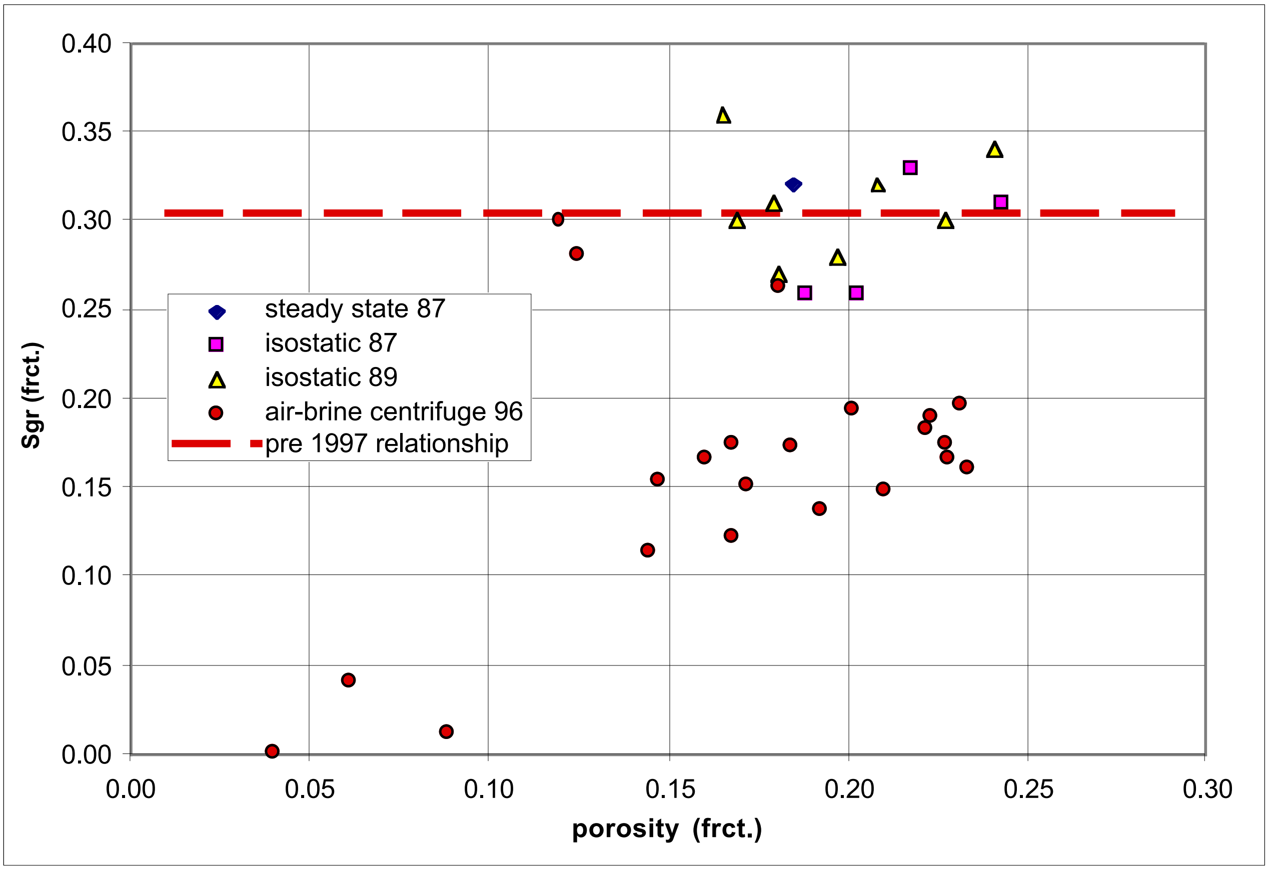

Figure 2a: Plot of porosity against laboratory derived residual gas saturations (Sgr). Data is the same as Figure 1 with the addition of air-brine centrifuge end-point data from 1996.

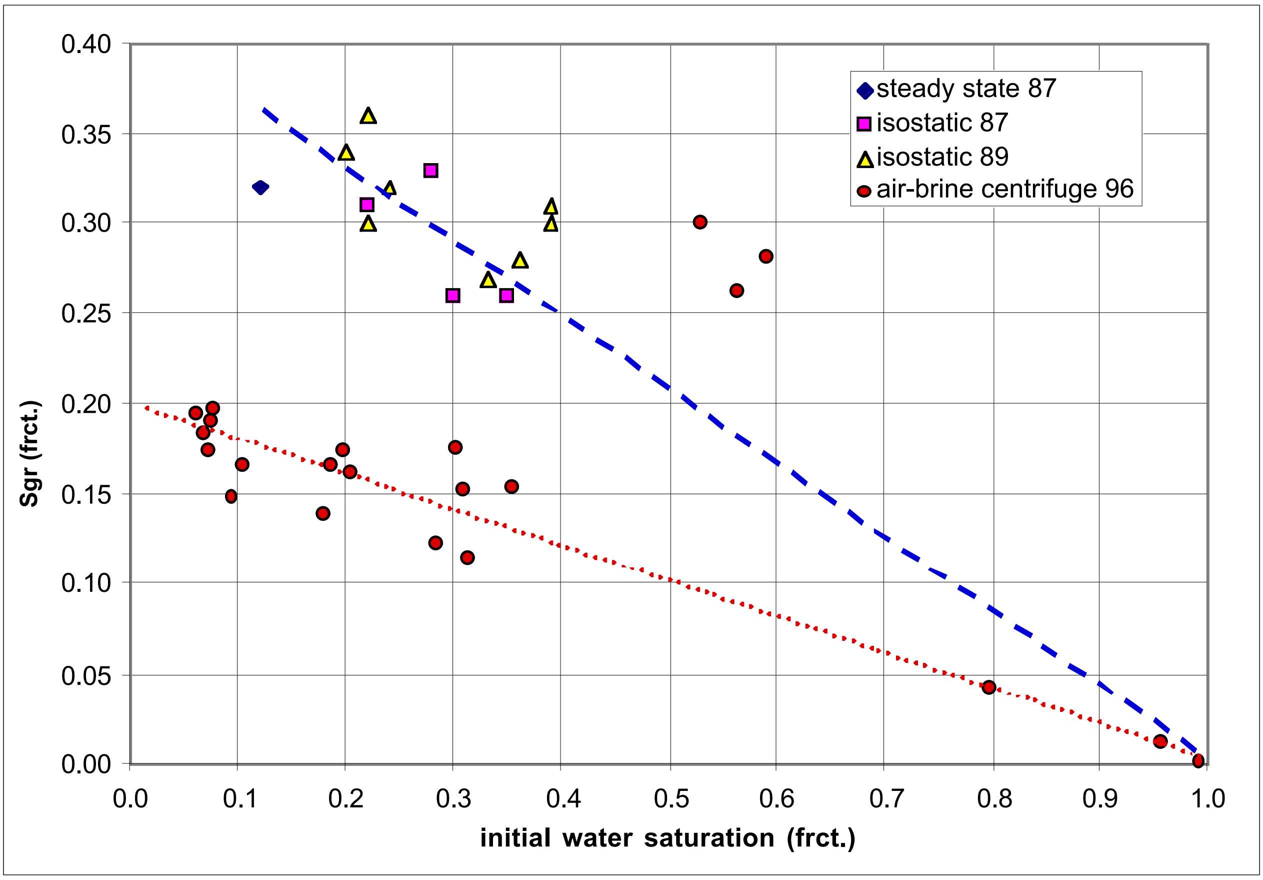

Figure 2b: Plot of initial water saturations against laboratory derived residual gas saturations (Sgr). Data is the same as Figure 2a.

saturated with water and the absolute permeability to water defined. Initial water saturation is established by oil flooding until brine production ceases. Next, water is injected at a constant rate of around 0.5 ml/min. Equilibrium is not reached. The volumes of produced and injected fluids are monitored together with the pressure difference across the plug, while keeping rate constant. When no more oil is produced, the effective permeability to water at residual oil saturation is determined.

Reaching irreducible water saturation by flooding is difficult, hence representative irreducible water saturations are not usually achieved. The combination of unfavourable mobility ratios and relatively high displacement rates leads to oil or gas being bypassed in samples, particularly if experiments do not use long enough displacement times. Consequently, both initial water and residual oil saturations in these experiments tend to be too high.

Centrifuge

In air-brine centrifuge experiments, a liquid saturated plug is placed in an air-filled core holder and centrifuged at constant speed. Production is measured as a function of time and the fluid relative permeability determined from the production data. To determine residual gas saturation, the sample at irreducible water saturation is fitted into a water-filled core holder and centrifuged at constant speed. When no more water is moving into the sample and/or gas production has ceased, the centrifuge is stopped and the sample removed for weighing to determine the remaining gas saturation.

With air-brine end-point experiments, the assumption of incompressible fluids made when interpreting the data is invalid. During water imbibition, a high pressure gradient will be generated in the sample causing gas compression. As a consequence, gas saturations will be reduced and gas displacement rates will vary with the pressure. These factors render gas-water centrifuge measurements suitable only for drainage experiments and undesirable for residual gas saturation measurement.

Following from the above, the ideal experiment to determine residual gas (or oil) saturations should use a centrifuge with two incompressible fluids. Hence, oil-brine centrifuge experiments were proposed and carried out in 1997. Light oil (decane) was recommended as a substitute for gas, since it does not influence wettability. At the same time, the use of incompressible fluids reduces uncertainty in the saturations so measured.

Following successful numerical simulation of centrifuge measurements in the deeper Maui oil reservoirs (Farmer et al. 2000), it was decided to acquire an additional comprehensive dataset in 1999 to allow numerical simulation of the C Sand oil-brine centrifuge measurements.

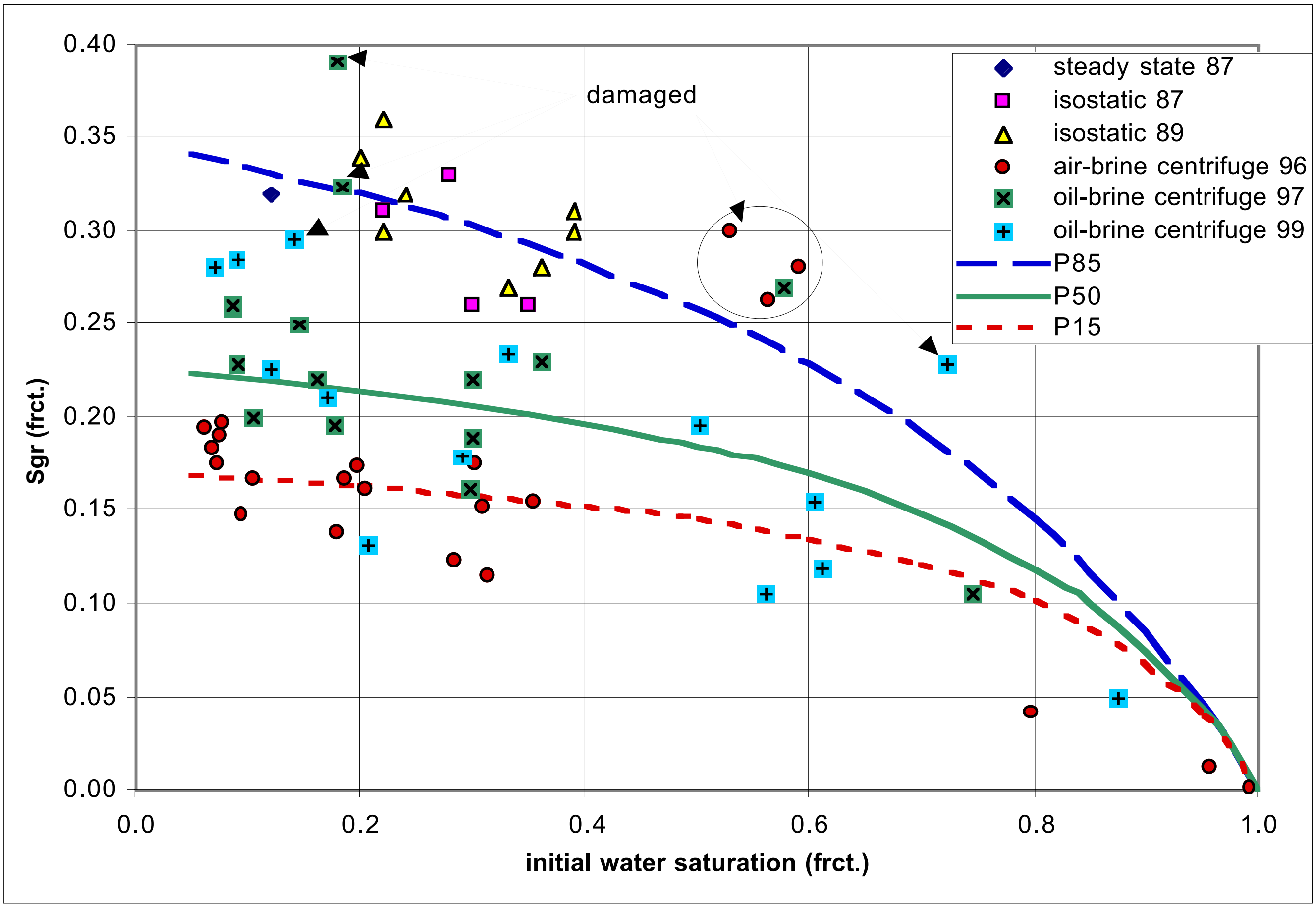

Figure 3: Plot of initial water saturations against laboratory derived residual gas saturations (Sgr). Data is the same as Figure 2a with the addition of 1997 and 1999 data.

Core analysis results

Results from the oil-brine centrifuge experiments carried out in 1997 and 1999 are shown in Figure 3 along with the earlier data. The data can be subdivided according to measurement type and three separate trends defined. Since the existing residual gas saturations for the Maui Field are based on the pre-1996 analyses, these have been used to construct the maximum residual gas saturations expected in the field. As discussed earlier, the air-brine centrifuge measurements are likely to underestimate the residual gas saturations, hence these analyses have been used to represent the low case residual gas saturation. The oil-brine centrifuge measurements are considered to provide the most likely estimate of residual gas saturations in the Maui C Sands. Those plugs showing evidence of damage after the experiments have been excluded from the regressions used to generate the lines.

It has also been recognised that the end-point oil-brine centrifuge measurements of residual hydrocarbon saturations may be too high. Work reported by Farmer et al. (2000) shows that simulation of the plug experiments leads to a more robust determination of residual hydrocarbon saturations. The simulation typically yields residual hydrocarbon saturations lower than the data prior to simulation. To date, these simulations have not been carried out for the Maui C Sands, but this work is underway.

A comparison between the average gas saturations for the Maui C Sand wells and the average residual gas saturations shows an increase in mobile gas saturations of 20% over the pre-1996 model, indicating the significance of these results.

In-situ residual gas saturations

Pulsed-neutron logs have been acquired at frequent intervals and in several Maui A wells since the early 1980s. Comparison between the logs from different times allows changes in gas and water saturations behind casing to be identified. Pulsed-neutron logs used in this "time-lapse" mode provide the only in-situ measurements of gas saturation changes in the Maui Field. These logs have been analysed to determine residual gas saturations seen in the field.

Evaluation of the PNC logs was carried out in six Maui wells with baseline data. Processing of the logs included depth-matching and averaging of passes, normalisation across water and gas bearing intervals expected to be unchanged and intervals of unchanged borehole content. Water and gas properties were determined from literature (Western Atlas 1988, Schlumberger 1991).

Changes in water saturations were estimated using comparisons of logs taken in the same wells at different times i.e. in time-lapse mode. The differences between the normalised logs have been used to estimate an uncertainty in water saturation changes of ±8% at porosities of 20%. Lower porosities have a higher uncertainty, owing to the smaller changes in PNC response and to the higher relative uncertainty in the porosity.

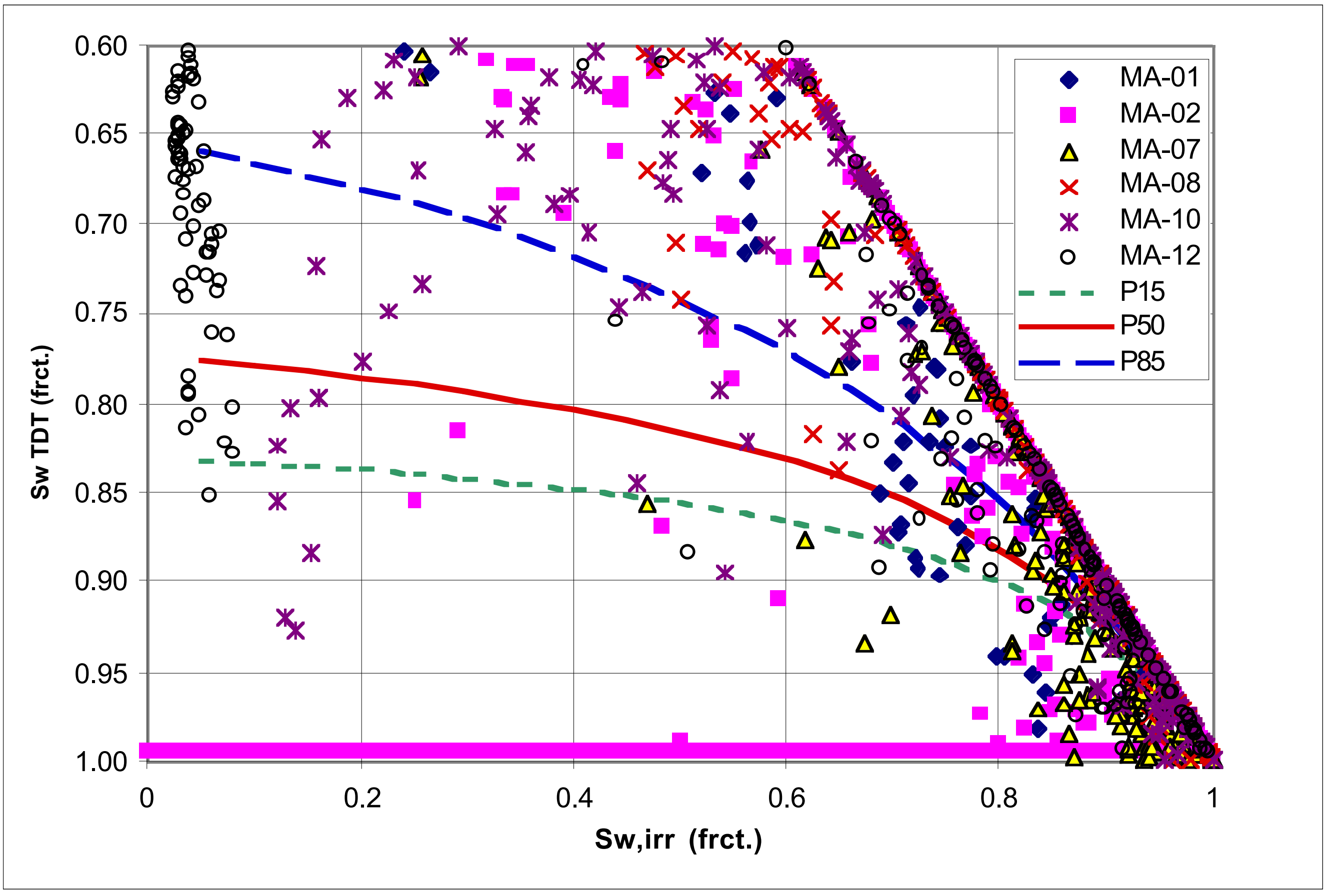

Figure 4: Plot of gas saturations from Maui A wells.

A plot of the most recent gas saturations from each well in an initial water vs residual gas saturation format (Figure 4) allows comparison with the core analysis derived residual gas saturation relationships. Since not all zones covered by the PNC logs are fully water swept, Figure 4 should be interpreted by looking at the lower envelope of the data for in-situ residual gas saturations. It is apparent that the residual gas saturation estimates from the laboratory measurements do not conflict with the in-situ data, especially when the log uncertainty is considered. It is also possible that the log data is suggesting that lower residual gas saturations than implied by the laboratory data may eventually be reached in-situ.

Conclusions

Residual gas saturation in the Maui Field is dependent on the initial gas saturation in the individual rock sample. Relationships representing the high, expectation and low case residual gas saturations have been derived directly from core data for the C Sands.

The use of oil-brine centrifuge capillary pressure curves to define residual gas saturations more accurately models what is expected in the reservoir than either air-brine capillary pressure curves or (un-)steady-state experiments.

Re-analysis and re-calibration of pulsed-neutron logs available in Maui-A has enabled in-situ estimates of residual gas saturations to be made. These measurements confirm that the laboratory estimates of Sgr are reasonable.

Recommendations

The C Sand core data currently being collected should be used to numerically simulate the plug experiments and derive more robust residual gas saturation estimates from the core data.

References

Farmer, R.G., Adams, S.J. & Verbruggen, R., 2000, State-of-the-art SCAL Experiments and Interpretation. New Zealand Petroleum Conference, 19-22 March 2000.

Firoozabadi, A., Olsen, G. & Golf-Racht, T. van., 1987, Residual Gas Saturation in Water-Drive Gas Reservoirs. SPE 16355, SPE California Meeting, Ventura California, 8-10 April 1987.

Land, C.S., 1968, Calculation of Imbibition Relative Permeability for Two- and Three-Phase Flow from Rock Properties. SPE 1942, Transactions Volume 243, June 1968.

Schlumberger 1991, Log Interpretation Charts. Schlumberger Educational Services.

Torsaeter, O., 1984, An Experimental Study of Water Imbibition in Chalk from the Ekofisk Field. SPE 12688, SPE/DOE 4th Symposium on Enhanced Oil Recovery, Tulsa, 15-18 April, 1984.

Western Atlas International, 1988, Atlas Wireline Services Log Interpretation Charts.

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