AN INTEGRATED PETROPHYSICAL ANALYSIS TO EVALUATE LOW RESISTIVITY LOW CONTRAST (LRLC) PAYS IN CLASTIC RESERVOIRS IN SE ASIA

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ABSTRACT

Low Resistivity (LR) and Low Contrast (LC) pays have been identified in many clastic and carbonate reservoirs all over the world. Typical LRLC zones in PETRONAS operated fields show resistivities of 2-4 Ohmm, which are similar to the resistivities of the adjacent shale beds and very close to the resistivities of the (fresh) formation water bearing zones(1-2 Ohmm). This study is focussed on the investigation of clastic reservoirs in the Malay, Sarawak and Sabah Basins, which are mainly shaly and silty sandstone zones, that were not obvious and not classified as "net pay" from previous conventional formation evaluation techniques. Based on an integrated petrophysical analysis of modern log data (including Nuclear Magnetic Resonance (NMR),Borehole Imaging), and Special Core Analyses (SCAL) data (including electrical, hydraulic and NMR properties), improved concepts and workflows were developed for the identification and evaluation of productive hydrocarbon bearing LRLC zones.

INTRODUCTION

There are two main types of problems associated with the identification of producible hydrocarbons and with the correct evaluation of LRLC zones:

1. **The water saturation S_w as derived from conventional resistivity logs is incorrect (too high)!**

This can be attributed to the following reasons:

1a. ResistivityLogging Tool related effects, i.e. the measured resistivity "R_t" is incorrect or not properly corrected for:

-Borehole, shoulder bed and invasion effects
-High dips or high well deviations
-Thin bed effects (laminations, anisotropy)

In most of the above cases, R_t has been underestimated.

1b. The resistivity of the formation water R_w is incorrect or unknown, e.g. due to variable salinity and/or variable ion composition.

1c. The saturation equation and parameters are incorrect, e.g. due to "Non Archie" more complex relationships between S_w and resistivity, reflected by variable or unknown:

- Cementation exponent "m", saturation exponent "n"
- Excess surface/interlayer conductivity effects (C_x)
- Cation Exchange Capacity (CEC)
- Conductive minerals (e.g. Pyrite, Siderite)

2. The water saturation S_w as derived from conventional resistivity logs is correct, but very high, and a conventional S_w-cutoff might eliminate these zones!

These rock type related high ("irreducible") water saturations can be due to:

- Grain size/pore size effects (high specific internal surface S_v)
- Bioturbation effects (high amount of bioturbated fine silts and shales)
- High amount of clays with high Cation Exchange Capacity (CEC, Q_v)

For these zones with a high amount of "capillary bound" water, it is crucial to determine up to which S_{wirr} the reservoir will be productive to establish permeability predictions based on the analysis of capillary pressure and relative permeability data, and to correlate these S_{wirr} with NMR derived T_2 spectra, for later calibration of NMR log derived continuous S_{wirr} and permeability profiles.

In many case histories, we have experienced a combination of several of the above causes for LRLC reservoirs, which underlined the need to first apply advanced resistivity modelling techniques to get reliable R_t values from logs, and to investigate alternative methods like NMR measurements for an independant evaluation of correct water saturations, and to predict the amount and type of mobile fluid phases.

The actual work program and the well selection for the ongoing LRLC study is mainly focussed to investigate the 2nd type of LRLC evaluation problems, i.e to understand and evaluate clastic reservoirs with very high S_{wirr}, that are nevertheless producing dry hydrocarbons. The project provides an integrated analysis of log and core data to derive revised log evaluation parameters, cut-off criteria for "net pay", and possibly modified saturation equations to assess LRLC pay zones.

WORK PROGRAM

1. Well selection

In a first step a number of key wells have been selected from fields with tested hydrocarbon flow from typical LRLC zones, i.e. resistivities of 2-4 Ohmm. The wells had, in addition to the conventional logging and testing data, a sufficient amount of cores and NMR logs, in order to investigate and reconcile the electrical, hydraulic (including capillary pressure curves) and NMR properties (e.g. T_2 distributions at different water saturations) from logs and cores.

If available, Image logs were used to identify zones of highly laminated thinly bedded sand/shale sequences.

2. Special Core Analysis

The SCAL investigations were concentrated on the analysis and reconciliation of three independent measurements to evaluate the irreducible water saturations S_{wirr} in case of LRLC effects due to the pore structure (see Fig.1):

1. NMR T_2-Spectra at different S_w.
2. Capillary Pressure Curves $p_c= f(S_w)$.
3. Electrical measurements , i.e.
   a. Conductivities C_o at different salinities/conductivities C_w of the formation water: $C_o= f(C_w)$, "Multi Salinity method".
   b. Resistivity Index R_t/R_o at different saturations: $RI=f(S_w)$.
   c. Cation Exchange Capacity (CEC) from the "wet chemistry method".

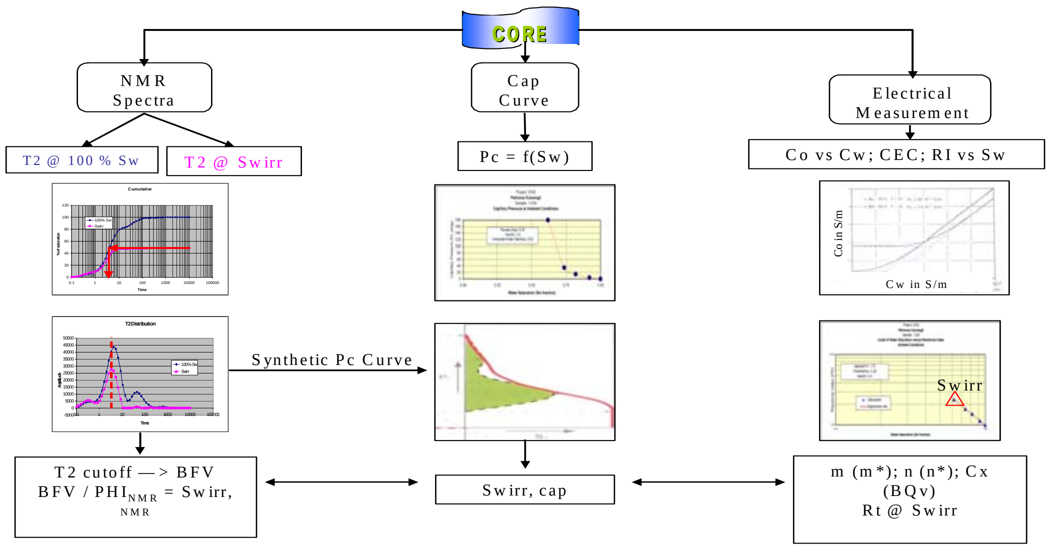

Figure 1. Workflow for the evaluation and reconciliation of irreducible water saturation Swirr from Special Core Analysis.

The results of the T_2 spectra at S_w=100%, were compared with the capillary pressures curves from the same plug, and also used to generate "synthetic" cap curves from the NMR spectra based on published algorithms (e.g. Li Guo Xin et al (2008)).
From the comparison of the cumulative T_2 distributions at S_w=100% with the cumulative T_2 spectra at S_{wirr}, T_2-cutoff criteria were defined to derive S_{wirr} from T_2 distributions. The resulting "Bound Fluid Volumes (BFV or BVI)" from the NMR core spectra were compared with the S_{wirr} from the cap curve and later applied to derive continuous S_{wirr} profiles from NMR logs in the uncored sections of the key wells based on analytical empirical functions or a statistical analyses based on Neural Net applications.
From the electrical resistivity measurements at different salinities and saturations, the formation resistivity factor (FRF), the excess conductivity C_x (or BQ_v), the "cementation exponent"(m or m*), and the "saturation exponent" (n or n*) were derived. The "traditional" relationships of log FRF vs log Phi or log RI vs log S_w were applied to test the validity and the potential application of different saturation equations, e.g. "Archie's Clean Sand Model" vs "Shaly Sand Models" (e.g."Dual Water", Waxman/Smits) or "Interlayer Conductivity Models" (Pape et al, 1987) for the later evaluation of the resistivity logs .

3. Well Log Analysis

In the first stage of this study, the log evaluations were focussed on the processing and evaluation of resistivity logs and NMR logs in order to derive and compare saturation profiles from these two independent log measurements (see Fig. 2).

For the resistivity logs some special processing and R_t -modelling was required to correct for borehole and environmental effects (including invasion and shoulder bed effects) and to generate reliable R_t profiles for the evaluation of S_w from different saturation models and equations. In hydrocarbon bearing reservoir zones above the

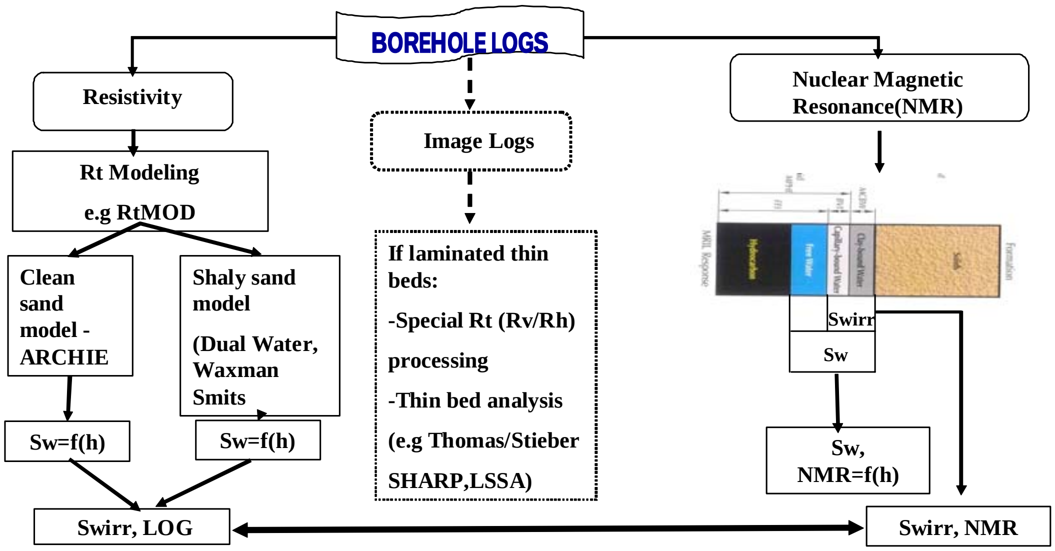

Figure 2. Workflow for the evaluation and reconciliation of irreducible water saturation $_{Swirr}$ from Resistivity Logs and NMR Logs.

identified FWL and above the assumed "transition zones", the S_{wirr} from the resistivity logs were reconciled with the S_{wirr} from the NMR log, by applying the T_2 cutoffs that have been established from the NMR core spectra . In case of major discrepancies between the electrical and the NMR derived S_w profiles, the T_2 cutoff and the electrical parameters (m, n, C_x) and the saturation equations have been varied until a best fit is achieved. The saturation profiles from the saturation height (SHF) modelling based on the capillary pressure curves have been used as a final reference and guidance until a reconciliation within +/- 5 saturation units is achieved.

EXAMPLES & DISCUSSION

Fig.3 shows a typical example of a LRLC zone with resistivities of 1.5-3 Ohmm, that has tested dry gas at very high log derived water saturations of S_w= 60-80%, even at rather high porosities of Phi=25-28% (with moderate average permeabilities of 5-50mD).The core was described as a silty/shaly argilliceous sand, which was confirmed by the high V_{sh} and V_{silt} fractions based on a GR and D/N crossplot analysis. The cap curve and the T_2 measurements confirmed the high amount of "irreducible bound water", and a type of a "bimodal" pore size distribution, where the majority of pores were classified as "micro"-pores (< 0.5 um), and a smaller fraction as "meso"-pores, (in the range of > 0.5 um to <5 um), that provide the flow path and storage for the gas. The Bound Water Volume (BVW) from the NMR log (Baker Atlas MREX) confirmed the high S_{wirr} evaluations at the top of the tested "sand", and also indicated that the further reduced resistivities below 1025m (s. Fig.3) are most likely due to lithology effects (nearly pure silt/shale) and not associated with a possible transition zone with moveable water. The saturation height function as derived from a cap curve (centrifuge air/brine) analysis confirmed a free water level (FWL) about 10m deeper than originally assumed from the analysis of the log derived saturation profiles, which resulted in a significant increase in reserves and a revised development strategy that justifies perforation to deeper zones than originally anticipated.

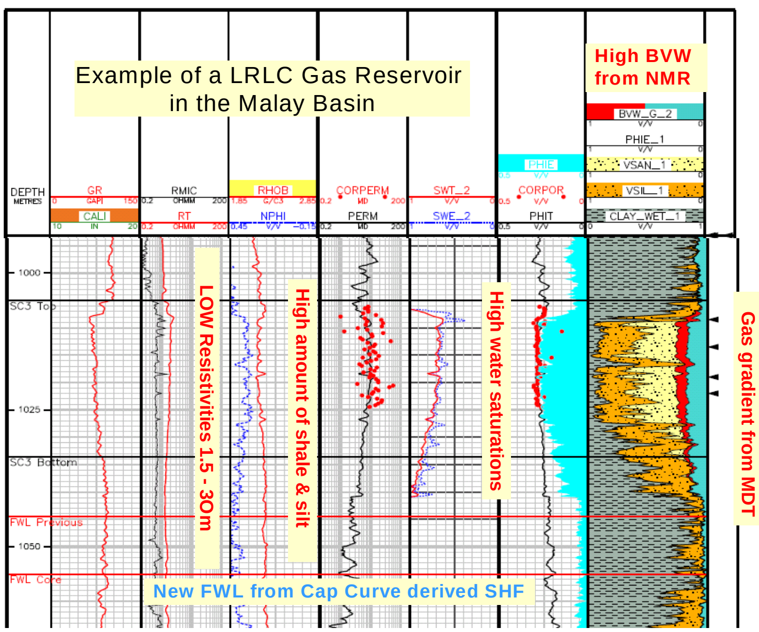

Figure 3. Log and Core results for a typical LRLC gas reservoir in the Malay Basin.

FUTURE WORK

After the evaluation and reconcilation of the "correct" S_w and S_{wirr} profiles from logs and cores, the next key step will be to assess and to predict the permeability K, i.e. the productivity of the LRLC zones. Hydraulic laboratory measurements of absolute permeabilities K_{abs} and relative permeabilities K_{rel}=f (S_w) will be investigated to derive correlations of S_{wirr} and possible other petrophysical parameters to generate continuous permeability logs.

Based on these permeability profiles new improved saturation height functions (SHF) can be generated from logs and will be reconciled with the SHF that were derived from the measured and/or synthetic capillary pressure curves.

CONCLUSION

Based on an integrated petrophysical analysis of modern log data (including NMR and Borehole Imaging) and advanced SCAL data, new workflows and correlations were established to reconcile electrical and NMR parameters, and to evaluate LRLC reservoirs in order to unlock additional reserves. For wells and fields with limited core and log data, a multivariate statistical analysis, including Neural Net solutions, were used for the calculation of true water saturations and to predict the amount and type of mobile fluid phases.

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