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Maximising NMR Log Interpretations in Thinly Bedded Reservoirs: An Example from Offshore Egypt

Introduction

Basan et al., 2003, focused on the laboratory phase of our work and discussed the issue of using default applications for NMR log interpretation and the importance of identifying the correct capillary pressure for calculating the T_2 cutoff. The laboratory phase contributed three important constraints on the interpretation:

1. Validation of the T_2 cutoff for BVI and BVM
2. Validation of the cutoff for clay-bound water
3. Recognition that the NMR Response Types in the channel and overbank deposits have different characteristics but still make up a continuum of pore geometries.

This paper shows how the T_2 distributions from the log were deconvolved (partitioned) into pore-size components generally equivalent to sand, silt and clay, to generate a high-resolution permeability estimate. This article focuses on the results. Details of the technique are contained in a separate paper by Lowden (2003).

It is important to point out that the process of deconvolving the T_2 distribution produces separate pore size populations, not grain size. Linking pore size to grain size (e.g. sands and silts) is convenient because it helps relate the results to the geology, but the link is an indirect one because sorting and diagenesis masks the grain size/pore size relationship. Relating pore size to grain size, with some certainty, therefore only works well where sediment is unconsolidated or where we know the diagenetic situation. The formation discussed in this paper is largely unconsolidated.

Interpretation Approach to Thin-Bedded Reservoirs

Preservation of vertical resolution

The value of NMR log data for formation evaluation and geological applications depends on vertical resolution and data quality. All interpretation processes after these factors depend on understanding the relationship between the NMR signal and rock properties. Default interpretations deal with data quality by automatically stacking the echo trains to increase signal:noise (S:N). NMR logs have an inherent vertical resolution that ranges between 6-inches (15 cm) and 2-feet (61 cm), depending on tool type. Stacking of course decreases vertical resolution, often rendering data unhelpful in thin-bedded sequences. The formation discussed here contains thin-bedded sands, which requires the maximum vertical resolution (6" in this case). In order to maximise vertical resolution we applied an echo-reduction filter, rather than depth stacking, to increase S:N. This reduces the number of points in each train, hence limiting the number of 'bins' in the T_2 distribution, but maximises vertical resolution.

Consequently, our approach is to forgo stacking and instead work at an individual echo train level. The process is to filter within the echo train, using either an echo-reduction or a time-filtering process to increase S:N. We only mention the process because the approach is critical for maximising the signal without compromising vertical resolution. However, the details of the process are beyond the scope of this paper.

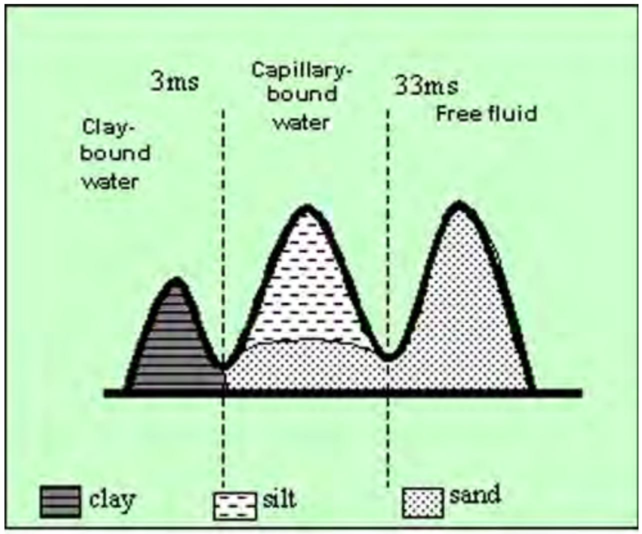

Figure 1. Schematic T_2 distribution showing separation of different pore size populations, corresponding to different lithologies

Developing the Thickness-Weighted Interpretation Model (TWIM©)

The TWIM approach models the different pore-size populations that constitute the T_2 distribution. We separated the T_2 distribution into three pore-size populations corresponding to: 1) free-fluid volume (=large pores); 2) bound-fluid volume (=small pores); and 3) clay-bound water (Fig. 1). These populations are loosely described as 'sand', 'silt' and 'clay'. The 'sand' contains free fluid and bound fluid, whilst the 'silt' contains only bound fluid.

The cutoffs used to separate clay, silt and sand are obtained from NMR core analysis. T_2 distributions from shaly samples show the signal for 'clay' is almost entirely below 3 ms (Figure 2a). A porous-plate desaturation experiment conducted on core samples from the channel sands showed bound fluid resides below 28 ms (Figure 2b). Sensitivity analysis revealed no significant difference in bound fluid using a 28 ms cutoff compared to the standard 33 ms, which is normally applied to NMR logs. We therefore applied a 3 ms cutoff to estimate pore volume associated with clays, and a 33 ms cutoff to estimate bound fluid. The NMR log captures only part of the free fluid due to incomplete polarization of gas. Consequently, we obtained the free-fluid volume by subtracting bound water (<33ms) from density-derived porosity. We calculated the average free fluid/bound fluid ratio for clean sands, identified where the GR log reads <50 API and then applied this ratio to the free fluid to obtain the proportion of capillary-bound fluid (3-33ms) associated with silt and sand.

Applying TWIM Approach: An Example from the Nile Delta

Initially, TWIM focuses on increasing the resolution and accuracy of the permeability estimate. Subsequently, however, the estimate of permeability provides the basis for isolating thin beds having hydrocarbon potential. The results from this technique provide a breakdown of the lithology in each CMR measurement, and three permeability estimates:

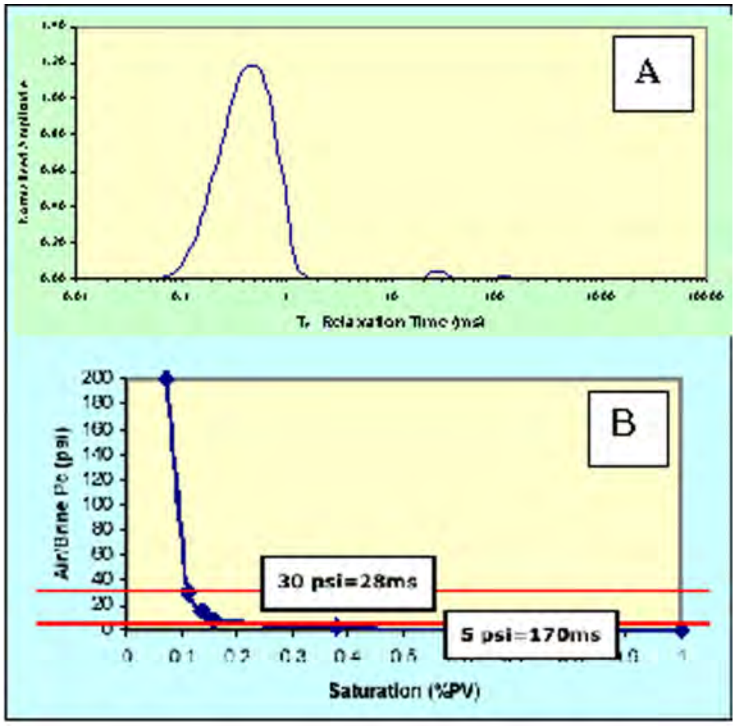

Figure 2. Laboratory NMR experiments and porous plate de-saturation curves were used to establish T_2 cutoffs for clay (A), and free fluid associated with sands (B).

1. The maximum permeability, which represent the sand component
2. The minimum permeability, which represents the silt component (clays are assumed tight)
3. The average permeability.

The TWIM method provides permeability values that match closely with core permeability in the thick upper sand (Figure 3, track 11). The model also identifies several thin sands above (marked *) and below (labeled 'A') the channel sand that have higher permeability than indicated by conventional NMR analysis.

The TWIM permeability estimate captures the dynamic range of the core data in the lower thin-bedded sand interval (unit labeled 'A', Figure 4, track 11). Previous interpretations showed the lower sand unit ('B') as a continuous sand body (track 4), whereas the TWIM interpretation reveals that the unit contains a tight, shaly layer ('C') that divides it into two parts, thereby revealing a potential partitioning of the main reservoir unit. The TWIM results also show that silts often have permeability up several milliDarcies, which offers the option to incorporate silt into estimates of net pay.

Water saturation was estimated from the NMR log by predicting the recovered gas volume using typical values of hydrogen index (0.5) and T1 (5s) for gas, assuming gas occupies all of the free fluid volume. The free fluid volume was obtained by subtracting bound water (<33ms) from porosity derived from the density log. Moveable water was identified where the measured volume of free fluid was greater than predicted recovered gas volume. Adding moveable water to bound water gives the total water saturation (Swt). Combining the hydrocarbon saturation (S_h=1-Swt) and density porosity with sand permeability and sand thickness from the TWIM approach allows calculation of recoverable hydrocarbon in thin-bedded intervals. Figure 5 shows estimated net pay over the lower thin-bedded sand

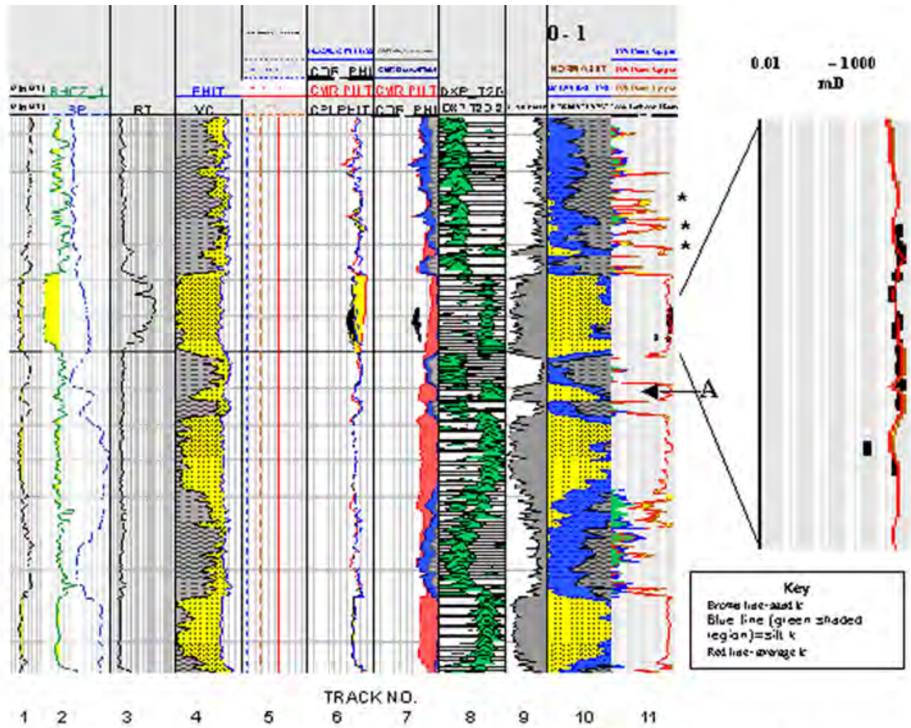

Figure 3. NMR log from the upper channel sand showing TWIM permeability plotted against core permeability (track 11). Track 10 shows the proportion of the pore volume associated with sand (yellow), silt (blue) and clay (grey) in each 6" T2 measurement.

interval, assuming S_h>15%, sand thickness>1", ϕeffective[1]>5%, and sand k_h>1mD. The results not only highlight the thick, gas bearing sands at the top and bottom of the section, which are evident from the density log, but also reveal the thin gas-bearing sands in the middle of the section that were previously unidentified.

Conclusions

The TWIM approach provides an improved method for NMR log interpretation in thin-bedded sequences by:

- Maximising the vertical resolution inherent in NMR log data
- Deconvolving the individual T_2 distributions to produce permeability estimates based on the proportion of pore-sizes contributing to this parameter instead of estimates based on a simple average.

Improving the resolution and accuracy of permeability estimates triggers the methodology for identifying potentially important hydrocarbon-bearing zones in thin-bedded sequences. Ultimately, the TWIM approach for NMR log interpretation offers a mechanism for validating the economic viability of unconventional reservoirs where tools or techniques fail.

References Cited

Basan, P. B., B. D. Lowden and J. Strobel, 2003 (abs), Maximising the value of NMR core data for geologists and petrophysicists. AAPG Ann. Conv., Barcelona, Spain.

Lowden. B. D, 2003, A new method for separating lithologies and estimating thickness-weighted permeability using NMR logs. 45th Ann. Logging Symp. Trans: Soc. Prof. Log Analysts, 2003.

[1] $\phi_{effective}=\phi_{total}$-clay bound water

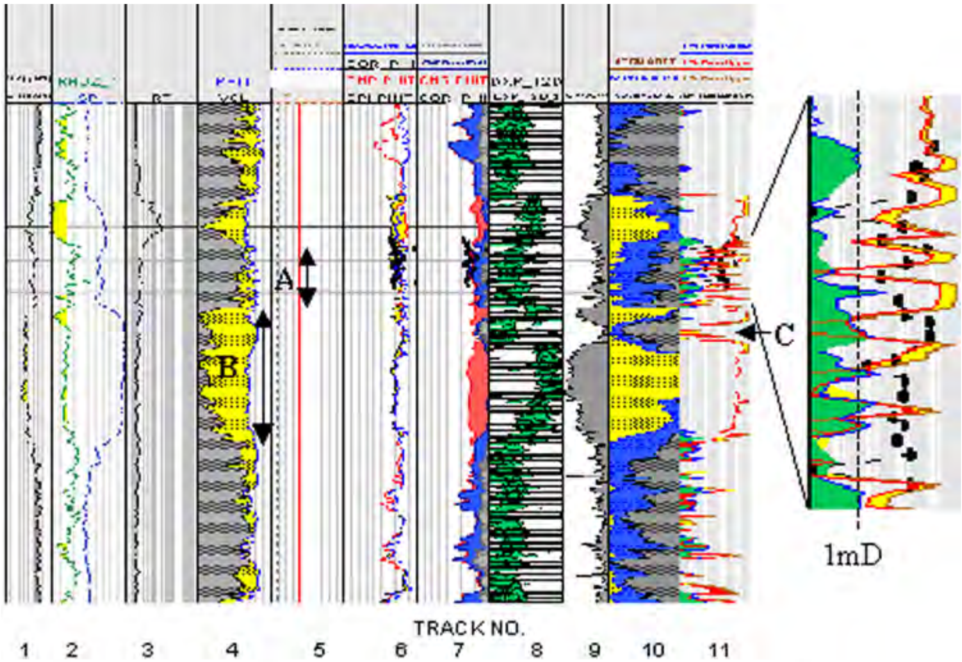

Figure 4. NMR log from the lower, overbank deposit showing the TWIM permeability plotted against core permeability.

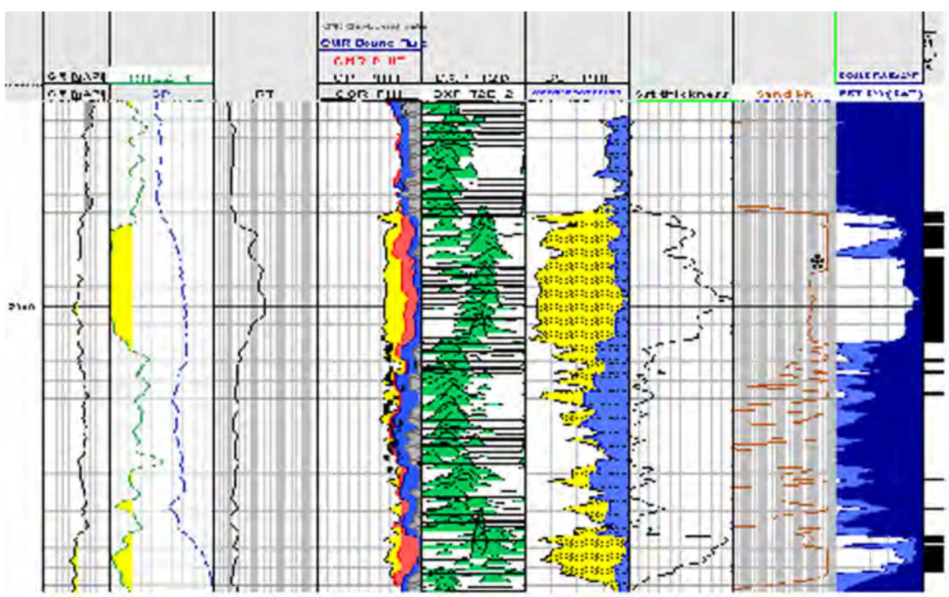

Figure 5. The thick, gas-bearing sands are evident from the density log. The TWIM model also identified thin, gas-bearing sands between these sands. The wet layer, labeled with an asterisk, is shale averaged out by the density log, reducing density porosity, and leading to the overestimation of NMR-derived Sw.