[PS]NMR Analysis of a Bimodal Pre-Khuff Clastic Pore System*

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Abstract

The pre-Khuff clastic reservoirs in Saudi Arabia are among the main gas resources in the Kingdom. The best/target prolific gas intervals are characterized from core studies as clean quartz with very low clay content and excellent reservoir quality. Yet, unexpectedly, despite the apparently high rock quality, water saturations—calculated from log data—over these intervals can be high. Special core analysis measurements, particularly mercury injection capillary pressure (MICP) and particle size analysis, show that the primary controlling factor on saturation is the variability in particle size, which results in a bimodal pore size distribution in these clean quartz rocks. The work presented here extends this core-based analysis of bimodality to improve its log-based characterization using nuclear magnetic resonance (NMR) data.

Preliminary results show that NMR T2 cutoff values are reasonably consistent between core samples having different rock qualities. Multiple echo-spacing experiments demonstrate that the internal magnetic field gradient is very low compared to the static magnetic field gradients of most available wireline NMR logging tools. This corroborated by integrated microscopy and quantitative mineralogy measurements that suggest small amounts of paramagnetic minerals. The absence of internal gradient is beneficial to the stability and constancy of downhole fluid diffusivity measurements. The resemblance between the NMR T2 distributions and the pore-throat size distributions obtained from capillary pressure curves suggests that NMR measurements can recognize micro- and the macro-pores. Also, this work concludes that modified parameters are required accurately to estimate permeability from NMR data in the considered formation.

The rocks studied in some cases showed dramatic differences between T2 distributions (pore size distributions) and MICP (pore throat distributions); independent rock quality parameters extracted from the two measurements show good correlation. This correlation proves that both parameters capture the general behavior of the rock and are insensitive to the details of either of the two distributions.

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factor is the variability in particle size, which gives these clean quartz rocks a bimodality in pore size distribution. The work presented here extends this core based analysis of bimodality to improve its log based characterization using nuclear magnetic resonance (NMR) data.

NMR analysis of a bimodal pre-Khuff clastic pore system

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Porosity-permeability

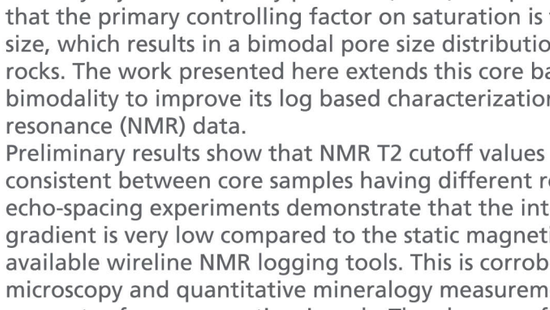

Figure 1: Permeability versus porosity for the plug studies.

T2 distributions

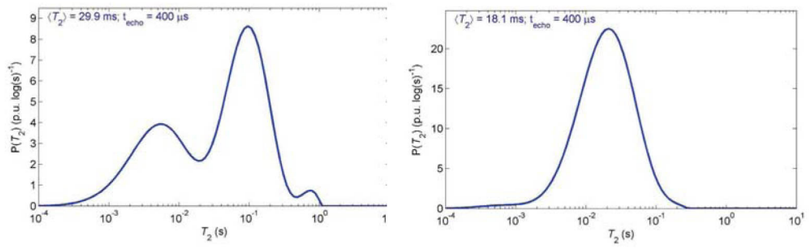

Figure 2: Two examples of T2 distributions for plug in the study, left, a clearly bimodal plug, right a unimodal one.

Internal gradients and cutoff

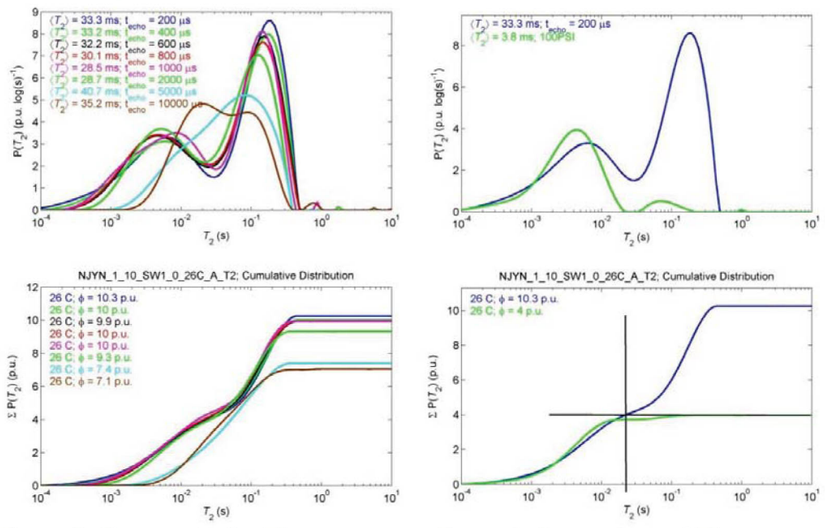

Figure 3: Changes to the T2 distribution shape and total detected porosity as a function of echo spacing are used to estimate internal gradients. In this case, virtually no changes for echo up to 1000 µs suggest negligible internal gradients.

Figure 4: Comparison of T2 distribution at Sw=1 and Sw=Swirr to determine T2 cutoff

Sample No	Cap.P(psi)	Swi @ 100 psi(NMR)	Cutoff (ms)
12	105	64.5	53
37	94	82.2	42
87	102	94.8	21
169	98	76.5	67
105	101	58.9	34
10	101	38.8	24
11	94	50.0	48
27	107	20.6	22
30	119	18.0	18
31	110	41.8	34
60	94	28.0	53
94	119	47.5	12

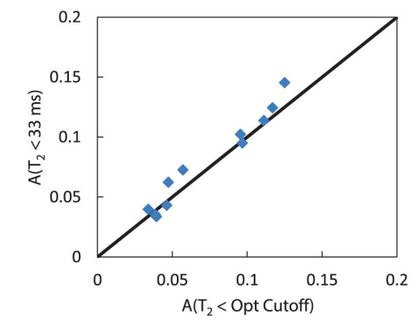

Figure 5: Comparison of the NMR T2 signal below 33 ms (standard cutoff) and the optimised cutoff for each sample. The consistency suggests that the cutoff-based bound fluid model is robust even in the presence of variations in the cutoff.

MICP vs. T2

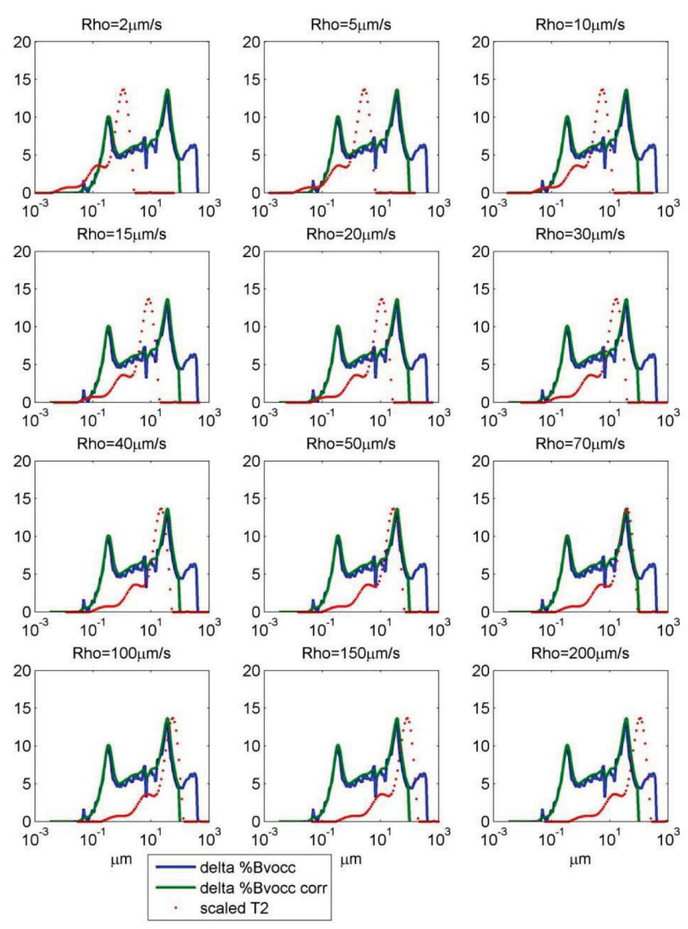

Figure 6: Comparison between T2 derived pore size distribution and MICP pore throat distributions. Each panel reports the raw data for MICP (in blue), the closure corrected MICP size distribution (green) and the pore size distribution obtained from NMR T2 with different relaxivity values (each panel representing one relaxivity). Note that there is no clear relationship between MICP and T2 peaks. Also, different peaks in the T2 and MICP match for different values of relaxivity, suggesting either different mineralogy or different pore size/body ratios. The range of obtained relaxivity, under the assumption of tubular pores and body to throat ratio of one spanned the range [5-70] µm/s.

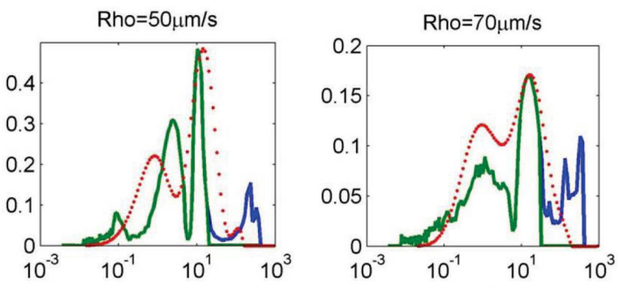

Figure 7: Examples for two different plugs. Left: a case where two peaks are clearly identifiable but different relaxivity is required to match each of them. The right panel shows two peaks that match using the same relaxivity.

NMR permeability (SDR and Timur-Coates)

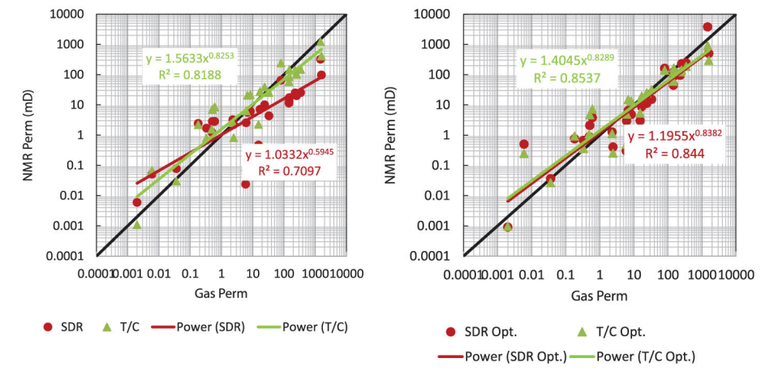

Figure 8: NMR derived permeabilities vs. gas permeability (both SDR and Timur-Coates). Left: Using standard parameters. Right: Using optimised parameters (see table).

$$k_{tim} = 10000 \cdot KTIM_A \cdot por^{KTIM_B} \cdot \left(\frac{FFV}{BFV}\right)^{KTIM_C}$$

$$k_{sdr} = KSDR_A \cdot por^{KSDR_B} \cdot T_{2lm}{}^{KSDR_C}$$

	Standard	Optimised
$KTIM_A$	1	0.043
$KTIM_B$	4	2.24
$KTIM_C$	2	2.3
$KSDR_A$	4	0.00015
$KSDR_B$	4	1.5
$KSDR_C$	2	3.9

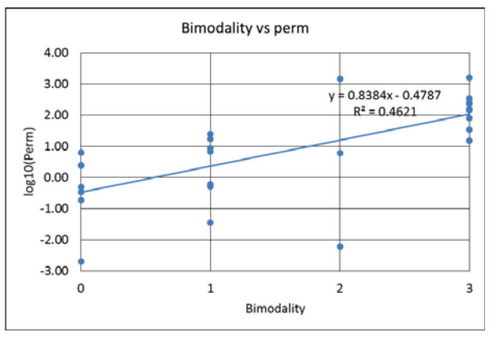

Figure 9: Relationship between an estimation of bimodality (from eye inspection) and permeability. Although highly qualitative and subjective this plot shows the plugs showing a higher degree of bimodality have higher permeability

Irreducible water saturation vs. Permeability

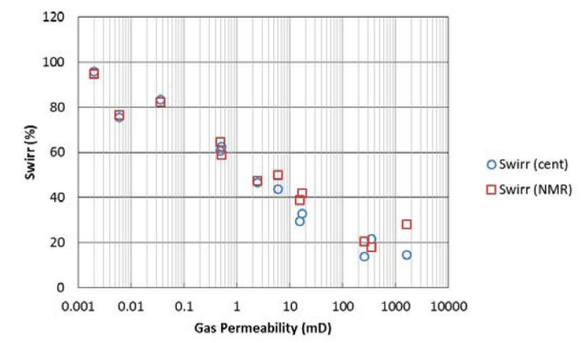

Figure 10: Relationship between permeability and irreducible water saturation after spinning in the centrifuge. Saturation from NMR (water filled porosity) and from produced fluid match very well for lower permeability samples while the scatter increases a bit for lower irreducible saturations (higher permeability samples).

Mineralogy effect

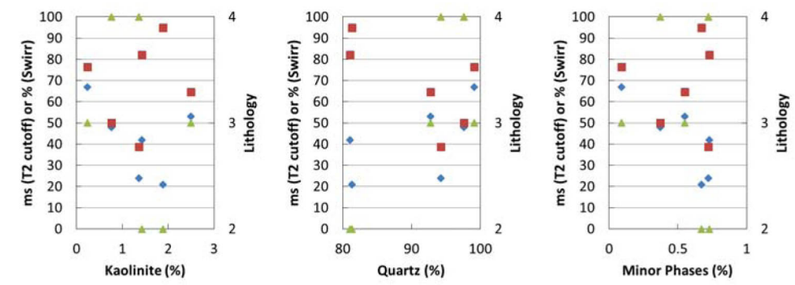

Figure 11: Relationship between chemical composition from Qemscan (left to right, kaolinite, quartz and minor phases) and measured parameters. The "lithology" is a dimensionless parameter extracted from MICP curves by inspection, and is an indication of the production quality of the rock. Note that none of the parameters correlate with the chemical composition.

Numerical simulations

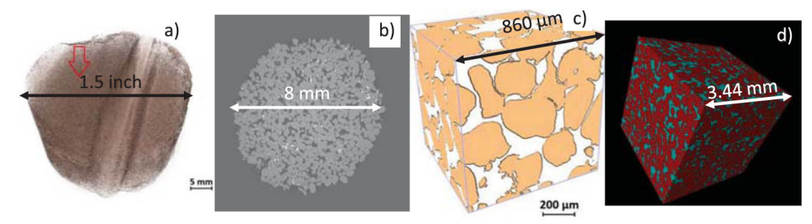

Figure 12: a) An optical image of a standard 1.5 inch plug and location of the mini plug extraction (8 mm diameter), b) an X-ray image of the mini plug, c) a lower resolution numerical model (pixel size 2.15 µm), and d) a higher resolution numerical model (pixel)

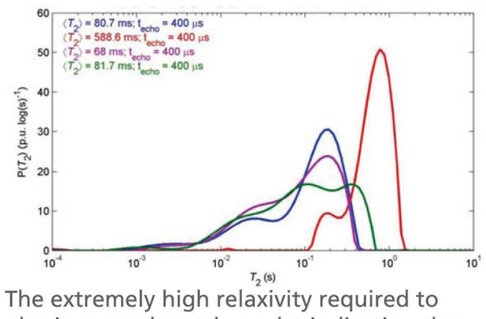

Figure 13: T2 distributions obtained by digital rock numerical modelling for the physical model in Figure 11 c). In red using the "initial" parameters T2, bulk = 3 s and ρ = 20 µm/s. In green still using T2,bulk = 3 s but ρ = 400 µm/s. In purple the T2 distribution simulated using T2,bulk = 0.6 s and ρ = 400 µm/s. This is the closest to the experimental NMR T2 distribution (blue)

The extremely high relaxivity required to obtain a good match can be indication that the isotropic sink model approach adopted in the simulation is too simplistic and requires the implementation of a more complex dynamics.

Conclusions and way forward

- Comparison between MICP and T2 indicates that the relaxivity values are not only very different among the different plugs, but also among different pore sizes within the same plug.
- There are cases where the MICP shows more peaks than the NMR T2. This can be due to lack of ability of NMR to resolve pores of very similar size, but can also be indication of presence of pores of same body size but different pore throat.
- Digital rock modelling reasonably predicts the shape of the T2 distribution, although to get a good match in terms of absolute T2 values, unrealistically high values for the surface relaxivity and low T2 bulk values need to be used. Since the technique converts the relaxivity as a probability for the spin to lose its magnetisation, the unrealistically high modelled relaxivity suggests the need for improvement in the probability conversion.
- The measured T2 cutoffs are consistent and close to the standard 33 ms despite the large pore size variations.
- Bound fluids computed from the NMR T2 spectrum using a single cutoff are very close to those obtained by desaturation suggesting the robustness of NMR-based of free fluid and permeability modelling.
- Within the limitation of spatial resolution, different sample size and limited number of samples investigated, Qemscan images and T2 distributions give compatible answers, while MICP is more complex. This is not surprising since MICP is sensitive to pore throat size while both imaging and T2 are sensitive to pore body size.
- Both SDR and Timur/Coates permeabilities correlate reasonably well with the one measured in the lab when using the standard parameters for sandstone (KTIMA=1 KTIMB=4 KTIMC=2) and (KSDRA=4 KSDRB=4 KSDRC=2)

A considerable improvement is achieved by permeability calibration. The optimized parameters are (KTIMA=0.043 KTIMB=2.24 KTIMC=2.3) and (KSDRA= 0.00015 KSDRB= 1.5 KSDRC= 3.9)

Both NMR based permeabilities (Timur-Coates and SDR) show a fairly good degree of correlation with the dimensionless parameter describing the rock quality, therefore NMR permeability can be a good indication of lithology variations.

No correlation has been found between cutoff, irreducible water saturation with the chemical compositions available from Qemscan.

A clear correlation has been found between permeability and irreducible water saturation.