ID No. 2004585

NMR core measurements for a better understanding of reservoirs with Complex mineralogy

S.S.Pabla, R.R.Tiwary, B.K.Saikia, Dr. K.J.Singh

CEWELL, ONGC, Vadodara, India

Pabla_ss@ongc.co.in

Introduction:

Unconventional hydrocarbon reserves – shale gas, heavy oil, and others – are increasingly playing a critical role in fulfilling our energy needs. Apart from these classical unconventional reservoirs, hydrocarbons are also found in volcano-clastic sediments. The evaluation of volcanoclastic reservoirs throws lot of challenges for most of the logging technologies, including nuclear magnetic resonance (NMR) logging. The lithology independent porosity from the NMR measurements is a critical input for reserves evaluation and was tried in volcanoclastic sediments of Western Onshore Field of ONGC to estimate free fluid porosity in a situation when all the other mechanism of porosity estimation fails due to multitude set of minerals encountered in such formation. But it was found that the standard T2 cutoff value, which compartmentalizes total porosity into bound and free fluid, could not be applied in the formation mentioned above. This value is highly dependent on type of mineral present, especially ferromagnetic minerals, and found to vary formation to formation. For realistic estimation of free fluid porosity, the NMR logs need to be calibrated with lab derived T2 cutoff values. Understanding the presence of different minerals can help in estimating accurate free fluid porosity.

Therefore, NMR measurements on core plugs were carried out in the laboratory for Olpad and Ankleswar formations of Padra field. These formations in this area are the typical examples of complex lithology where log interpretation is a highly challenging job. Olpad formation, which is volcanoclastic sediment, is characterized by its composition of various minerals and clay. Ankleswar formation on the other hand is highly argillaceous and it also makes the log interpretation difficult.

NMR THEORY

A CPMG sequence (Carr-Purcell-Meiboom-Gill) is used to measure NMR T2 distributions of core plugs in saturated state. In a porous rock system, there will be a continuous range of pore sizes, rather than several discrete sizes. This means that the CPMG echo-train comprises of a continuous range of relaxation times. Each pore-size has a distinctive T2 value. The oscillating nuclei diffuse randomly in a fluid, and in a porous system some will come in contact with the pore surfaces, allowing them to relax (by energy transfer to the pore wall). In the fast diffusion limit, the relaxation time observed experimentally is an average relaxation time for all the nuclei in the pore. Therefore in either a small pore or wetting film, the nuclei are more likely to interact with the surface, and so the average relaxation will be faster and the time for relaxation shorter than in a large pore. The echo-train corresponding to one particular pore-size will have a characteristic T2 value and signal amplitude proportional to the amount of fluid contained in pores of that size.

NMR equipment and techniques (Methodology)

NMR experiments have been performed on a standard low frequency (2 MHz) bench top magnet system. *T*2 distributions have been acquired using a standard Carr-Purcell-Meiboom-Gill (CPMG) sequence, with different inter-echo (echo spacing) times from a minimum of 200 µs to a maximum of 10 ms. Overall duration of the CPMG echo train was kept constant equal to 10 s. To allow full recovery of the longest expected relaxation components in the samples, a recovery delay of 13 s was used in all the experiments. This allows a polarization of 99.3% for *T*1 components equal to 2.6 s, the expected value for bulk water.

Gradient coils are used to generate a linear change of magnetic field across the length of the sample. By this method, the signal is encoded as a function of frequency received into the spectrometer. A transform of the data provides the spatial variation of porosity because the applied field gradient is known, and thus the frequency corresponds to distance.

An estimate of the size of the average internal gradients is possible by use of the diffusion-based T_2 expression,

$$\frac{1}{T_{2D}} = \frac{1}{12} \cdot D \cdot (\gamma \cdot Grad \cdot t_e)^2 \cdot$$

D is the diffusivity of water, γ is the gyromagnetic ratio of the hydrogen nucleus, *Grad* is the internal gradients of the sample, and *te* is the inter-echo spacing.

From the expression above, and having at least two measurements, we can determine the estimated average gradient as:

$$G = \sqrt{\frac{\frac{1}{T_{2,t_{e,1}}} - \frac{1}{T_{2,t_{e,2}}}}{\left(t_{e,1}{}^{2} - t_{e,2}{}^{2}\right) * \frac{1}{12} D\gamma^{2}}}$$

To determine the T2 cutoff values, the plugs are de-saturated in a centrifuge and NMR is acquired after spinning. The *T*2 distributions at *Sw* = 1 are then compared to the distributions after desaturation by spinning in the centrifuge.

Results:

In Table 1 are presented the measurements of the plugs after trimming and the basic petrophysical properties of the samples. The trimming was required to obtain appropriate dimensions for centrifugation. Gas permeability was by helium, on fully dried samples, after all the NMR and centrifuge measurements were made.

NMR Sample No.	Dry Weight (gm)	Length (cm)	Dia-meter (cm)	Bulk Vol (cc)	Grain Density (g/cc)	Gas Poro-sity (%)	Gas Perm-eability (mD)	Remarks
19	178.278	6.014	3.775	67.325	2.78	4.69	--	Vuggy / fractures
281	148.154	6.009	3.779	67.388	2.86	23.21	18.8	Vuggy / fractured. Vugs filled with teflon tape
311	93.175	4.835	3.882	57.216	2.67	39.06	--	Damaged during cleaning. Repaired Teflon tape and heat shrink wrap
312	128.187	5.998	3.777	67.208	2.92	34.78	31.2	Very vuggy. Vugs filled with Teflon tape
55	99.008	5.993	3.773	66.995	2.76	46.38		broken edges/ fractured
5	78.036	5.034	3.737	55.219	2.82	49.97		broken edges/ fractured

Table 1: Data of the samples.

Full suite of NMR measurements at *SW* = 1

T2, 1D Profile, Diffusion-T2, and T1-T2 with inter-echo spacing of 400 μs

Full suite of NMR measurements on the cores at Sw = 1 are shown in figure 1. In the top left panel is the *T*2 distribution from the CPMG (in blue) along with the distribution calculated as the *T2* projection of the *D*-*T*2 map (dashed black). In all six core plugs, the majority of signal is at short *T2* with some porosity present also at longer relaxation values. The short *T2* values arise from small pores, high internal gradients, or both. However, it has been found that both effects are present in all except one core plug (311) which shows modest internal gradients.

The top right panel shows the 1D porosity profile along the length of the plug. *It is noted that the only signal visible in this plot is the porosity that is FREE of any internal gradients.* The left side of each 1D profile plot is at the bottom of the plug, while the right side is the top of the plug. The profile is fairly uniform (as for example with plug 5); while in other cases there is more structure. The interpretation is that there is non-uniform porosity, reflecting the large cavities in the samples. As a quality control check, it is noted that the presence of vugs in the 1D profile should also result in a *T2* distribution signal at around 1 s, close to the bulk *T2* value of water and such a correlation is seen for plugs 281, 311 and 312.

The *D*-*T*2 maps are shown in the bottom left panel. The color coding represents the amount of porosity allocated to each part of the map. No color means zero porosity, and the color scale ranges from blue (low porosity) to green (high porosity) relative to the maximum amplitude for that graph. In all cases the total amplitude is small relative to the total porosity. The only *D*-*T*2 projections that show enough signal are for samples 281, 311 and 312. The other samples either are too low in porosity (sample 19) or they have extremely high internal gradients that cause a loss of nearly all signal before the diffusion encoding data is acquired (19, 5, and 55). The comparison of signal for the standard *T2* and the *D-T2* experiment can be seen in the upper left hand plots, where the *black curve is the projection of the D-T2 map along the T2 dimension.* We note that signal in these maps near the bulk water region must be unaffected by the extreme internal gradients or else the signal would not appear at the bulk water *T2*. It is thus *consistent* that the water correctly plots at, or just below, the water diffusivity line, as expected for partially restricted water.

The bottom right panel shows the *T*1-*T*2 correlation experiment map. The signal is expected to lie in between the two black lines (representing the lines for *T*1 = *T*2 *and T*1 = 2 x *T*2). Most of the results follow this expected behavior, with the shortest component having a higher value than the longer ones. However for plug 312 the *T*1/*T*2 ratio reaches values of about 10. It is noted that all *T2* laboratory measurements are in the presence of zero *applied* magnetic field gradient. Thus, a *T*1/*T*2 ratio of 10 is extremely high, possibly indicating high magnetic impurities that preferentially reduce *T2* relative to *T1*. While this observation is not entirely understood, sample 312 shows the highest estimated average gradient of magnetic field.

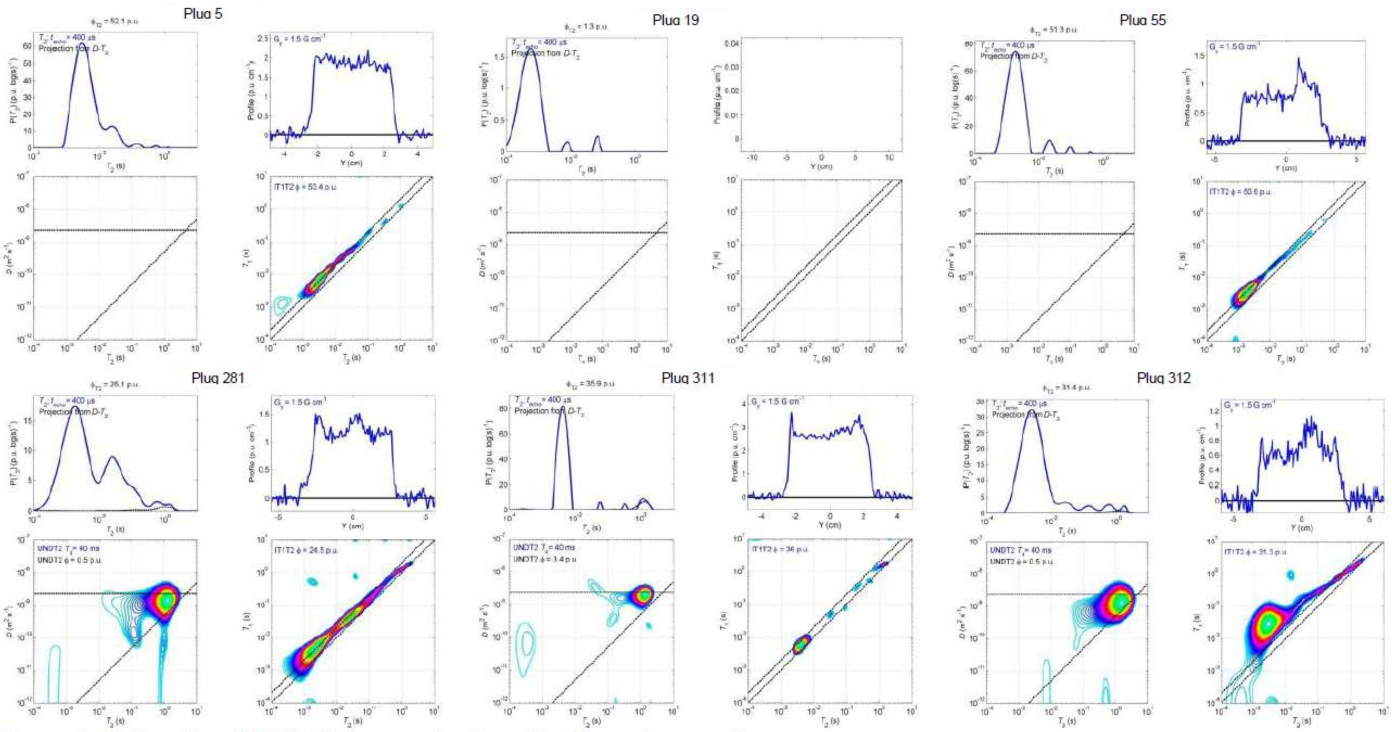
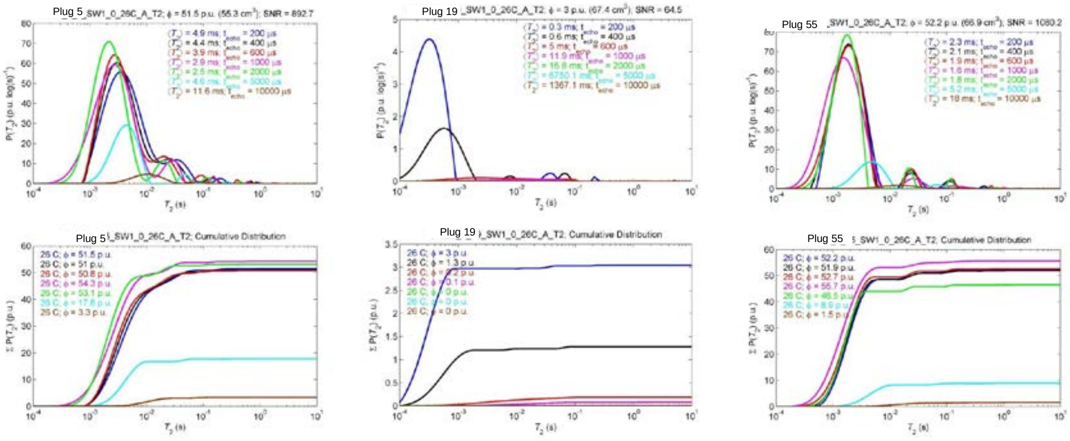


Figure 1. Full suite of NMR data acquired on the $S_W = 1$ core plugs.

NMR *T*2 measurements at *SW = 1* with multiple inter-echo times

*T*2 distributions acquired on the plugs using different inter-echo times (from 200 µs to 10000 µs) are shown in Figure 2. The top-most plot in each figure shows the *T*2 distributions, while the bottom plot shows the cumulative sums. The cumulative sums are simply the *T2* distributions of the top panel integrated along the *T2* dimension. The *T*2 distributions show the expected shift in the *T*2 domain, whereas the cumulative sums highlight changes in overall signal amplitude.

The *decrease* of the overall total signal amplitude (the asymptotic value of the cumulative sums) as the inter-echo time *increases* is an indication of the presence of considerably strong internal gradients. The most remarkable results are for plug 19. On this sample, the signal decreases by half or more when increasing the value of inter-echo time from 200 µs to 400 µs, and virtually disappears when using 600 µs. Similarly for plug 312 signal decreases strongly at an echo spacing of 2 ms. The average estimated mean value of the internal gradients is given in Table 2.



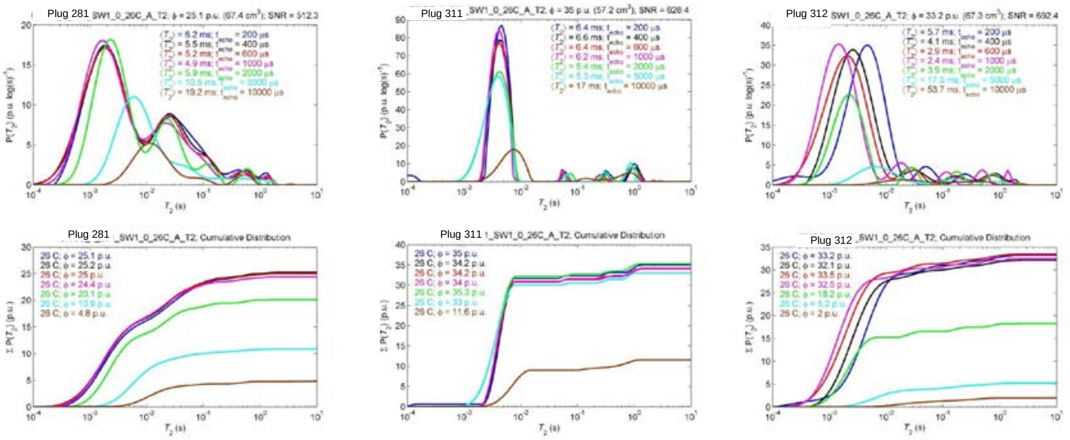


Figure 2: NMR T2 measurements on the core plugs at S_w = 1 with multiple inter-echo times

Desaturation

The plugs were de-saturated in a centrifuge and the plots in Figure 3 show the capillary pressure curve during centrifugation. All the plugs have been spun to 75 PSI in 4 steps (10, 25,50 and 75 PSI).For two plugs (5 and 311) NMR has been acquired after 25 PSI and 75 PSI, for the other 4, NMR was acquired only after the final step at 75 PSI.

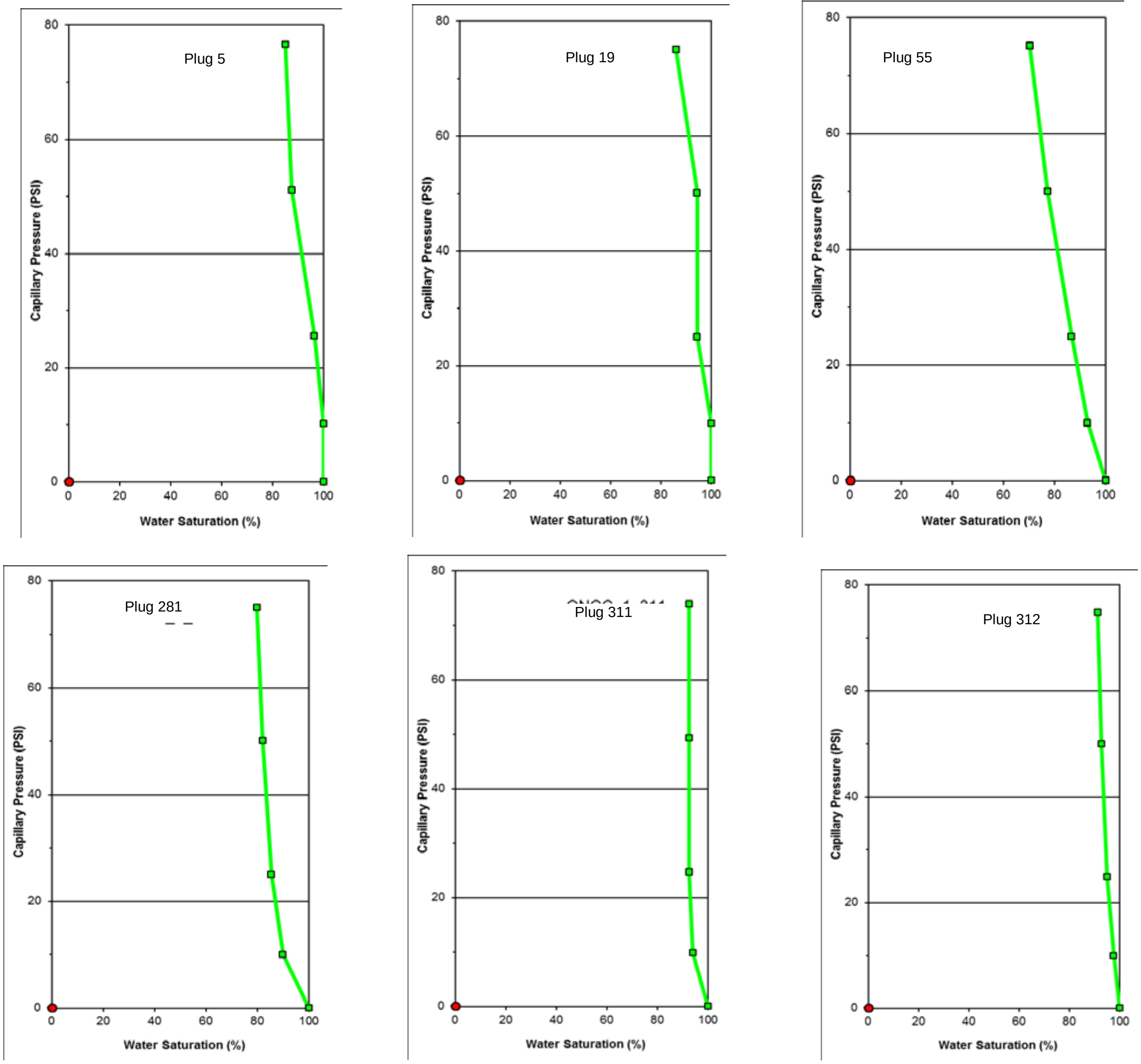


Figure 3: Plots showing Capillary pressure curves during centrifugation

NMR after desaturation

The *T*2 distributions at *Sw* = 1 (blue) are compared to the distributions after desaturation by spinning in the centrifuge at 25 psi (green, only for 2 plugs) and 75 psi (black). The top panels show the *T*2 distributions and the lower panels show the cumulative porosities.

The most salient feature is that the distributions change very little from *Sw* = 1 to *Swirreducible*. This means that the irreducible water saturation is high. To determine the cutoff value, the cumulative distributions (lower panels) are useful, since they allow for a simple graphical determination of the cutoff values. The cutoff is simply the *T2* value where the black (*Swirreducible*) curve asymptote intersects with the blue (*Sw* = 1) curve.

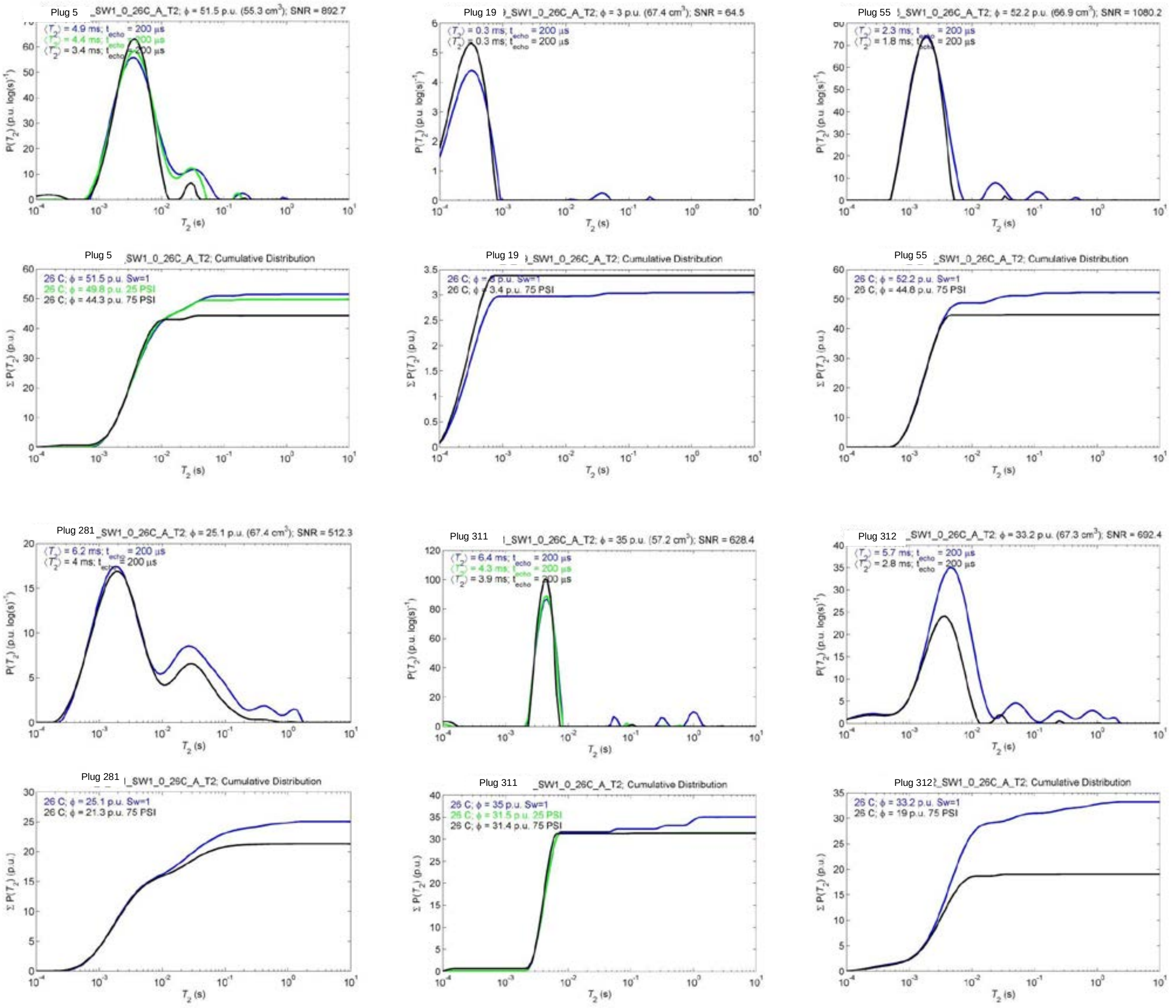


Figure 4: NMR T2 distributions on the core plugs at S_w = 1 compared to distributions after desaturation

From the figures above, we can see that the cutoff values for these plugs are extremely low, consistent with tight rocks and high magnetic field gradients. Estimated values for the bound vs. free fluid cutoff are given in Table 2.

Plug number	*T2* cutoff value [ms]	Estimated mean value of the internal gradient (G/cm)
5	10	810
19	< 1	> 2000 (poor snr)
55	3	380
281	10	550
311	5 to 15	< 30
312	2 to 3	2400

Table 2: T2 cut-off values and average internal gradients

For plug 19 the signal at *Swirreducible* is higher than for *Sw* = 1. The *low porosity* (3 pu) and *short relaxation time* (well below 1 ms) result in systematic error on the order of 0.5 pu. For this reason a cutoff value < 1 ms, the maximum *T2* in this case has been given.

The comparison to logging tools clearly requires a short echo spacing to characterize the formation as free of internal gradient effects as possible. Additionally, these cutoffs are likely to apply only within certain zones, and a careful evaluation of rock types within the formation is expected to be important.

Conclusions

(1) The *T*2 cutoff values are found to be very short for all the plugs and less than 15 ms in all the plugs.
(2) The saturation after spinning the plugs at 75 psi in air is very high for all the plugs, indicating that most of the fluid in the plugs is bound.
(3) The internal gradients in most of the six plugs measured by suites of CPMGs in this study are very high. Plug 311 shows a very low internal gradient, but is still very tight and thus still shows a short *T*2 cutoff.
(4) The *diffusion-T2 and T1-T2* data, acquired for *Sw = 1*, show minimal signal, which comes from large-pore free fluid unaffected by the internal gradients. Additionally, the shorter relaxation times of the *T1-T2* plots indicate very high intrinsic *T1/T2* ratios, which are coincident with high magnetic field gradients.
(5) The saturated core plugs show heterogeneity along the plug axis, with evidence of vugs which are confirmed by visual inspection and the presence of bulk water *T2*.

Acknowledgements:

Authors are thankful to the management of ONGC for providing all the help in publishing this paper. Thanks are also due to Mr.Andrea Valori, Nate Bachman & Farhan Ali of M/s Schlumberger Dhahran Carbonate Research Center and Mr. Udit Guru from Schlumberger Asia Services, Mumbai for carrying out the study on core samples.

References:

1. GRP002-0712: NMR core measurements for a better understanding of volcano-clastic reservoirs and reservoirs with complex mineralogy- Unpublished report of Schlumberger 2013, Andrea Valori, Nate Bachman, Farhan Ali, Udit Guru.
2. Developement of interpretation technique for Ankleshwar and Olpad formation in Padra field, Cambay Basin, B K Saikia & R Solomon, Unpublished report of CEWELL, 2010.
3. ‘NMR Relaxivity Grouping or NMR Facies Identification is Key to Effective Integration of Core Nuclear Magnetic Resonance Data with Wire-line Log’, Henry A. Ohen, Paulinus M. Enwere, and Jerry Kier, Core Laboratories.(SCA-9942).