COMPARISON OF NMR LABORATORY AND LOG MEASUREMENTS IN A BITUMEN SAND

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ABSTRACT

The study reported here presents the analysis of raw NMR log data performed in a bitumen sand deposit zone and the comparison with NMR laboratory experiments performed on plugs and processed with the same software. The main objectives are to obtain reliable estimations of porosity and water saturation, the later being critical when designing steam injection processes. Due to the extremely high viscosity of the bitumen considered and the low temperature of the reservoir, the NMR laboratory and log measurements strongly underestimate porosity. The use of special pulse sequences greatly enhances the resolution of short relaxation times, yielding laboratory and log bitumen signatures that are totally coherent at reservoir temperature. From the laboratory experiments performed on preserved samples, we deduced the total amount of water and bitumen by varying the temperature of the sample. This simple procedure allows the separation of the bitumen and water signals at low temperature and the determination of porosity at elevated temperature. The latter is in agreement with the density-neutron porosity. The laboratory and log data disagree on the water saturation.

INTRODUCTION

The detection of bitumen is now possible with the most recent NMR logging tools but requires non-conventional analysis methods. Schematically, the case of bitumen is to some degree simpler than medium to heavy oils because the overlap between water and bitumen is limited (Figure 1). With very heavy oils, the NMR response is indeed in the lower range of relaxation times (<1 ms for viscosity >100,000 cp) due to the approximate inverse proportionality to viscosity [1]. In addition, bitumen sand deposit are often located at a small depth with low temperature. For water located at the surface of the grains, the lowest relaxation times that can be reached is of the order of 1 ms and is characteristic of clays (Figure 1). Therefore, a contrast between oil and water is expected. Another important aspect of the in-situ measurements in bitumen sands is that no invasion is expected. The main difficulty reported here is related to the fact that the relaxation times of bitumen are at the limit of detection of standard NMR laboratory and logging instruments.

This study is an attempt to reconcile log and laboratory data in a bitumen sand deposit located in the Surmount area (Canada). We describe first the logging data set. Then, we describe the laboratory measurements on a bitumen sand sample and the calculation of porosity and saturation. We consider also the longitudinal T_1 and tranverse T_2 relaxation properties of the bitumen alone to estimate polarization corrections.

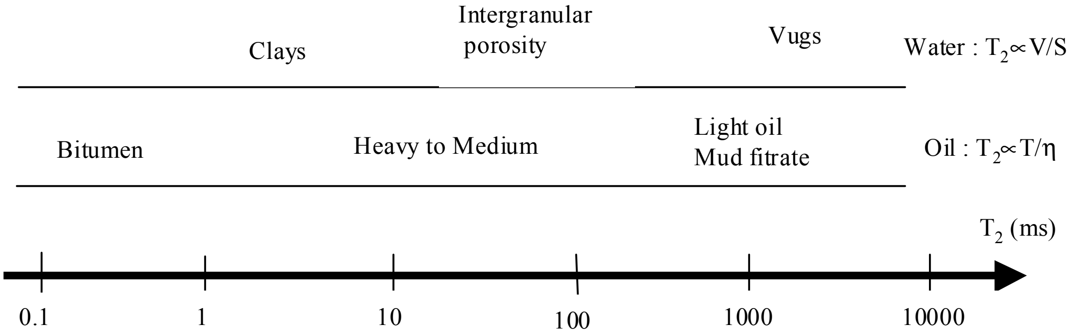

Figure 1: Range of NMR relaxation times as a function of pore structure and oil viscosity, assuming a water wet situation. Bitumen is at the limit of detection of standard NMR instruments.

NMR LOGGING DATA SET

A composite log (neutron-density-resistivity-NMR, Figure 2) has been performed over the depth interval [320-420]. From the standard log display (not shown entirely in Figure 2), three zones can be distinguished:

- a water zone (330-342 m) at the top of the bitumen zone of interest. The relaxation time distribution peaks at about 200 ms. Shorter components in the distribution indicate the presence of clays in small amounts. For a sand structure with a relatively uniform grain size distribution, one expects to observe a porosity in the range of 30-45 %. This is indeed found by the NMR and density-neutron tools (about 35 %),
- a clay rich zone at the bottom (400-404 m) with a unimodal distribution peaking at about 2 ms, a relaxation time typical of clays,
- the bitumen zone of interest (342 – 400 m). The bitumen has a density of 1013 kg/m^3 and is rated 8° API. This zone is characterized by a clear bi-modal distribution peaking below 1 ms and around 100 ms. Because the bitumen is known to be very viscous and close to a solid at reservoir temperature, the bitumen relaxation time is expected to lie below 1 ms and therefore, the lowest peak can clearly be associated with bitumen. The second peak at 100 ms can be associated with water if one assumes the sand to be water-wet, which is often the case in bitumen or heavy oil sand (Butler, 1997).

To obtain the amount of bitumen, it is customary to associate the porosity deficit between NMR and density-neutron to bitumen, assuming that no bitumen signal is detected. However, bitumen is obviously detected and one should not take into account the peak at low relaxation times. For example, focusing on the depth interval [371–371.5 m] where a sample is available (see section Laboratory measurements), the amount of water deduced from the second peak is 8.5 p.u. and therefore, the water saturation deduced from the density neutron porosity is 8.5/35=24 %.

It is the purpose of this paper to compare in detail the porosity and saturation obtained from the NMR log with NMR measurements performed on two preserved samples. Obviously, porosity and saturation have strong impact on reserve estimates, but the water saturation has also a strong impact on the design of the recovery process. High water saturation implies that steam injection will be much less efficient in heating the bitumen.

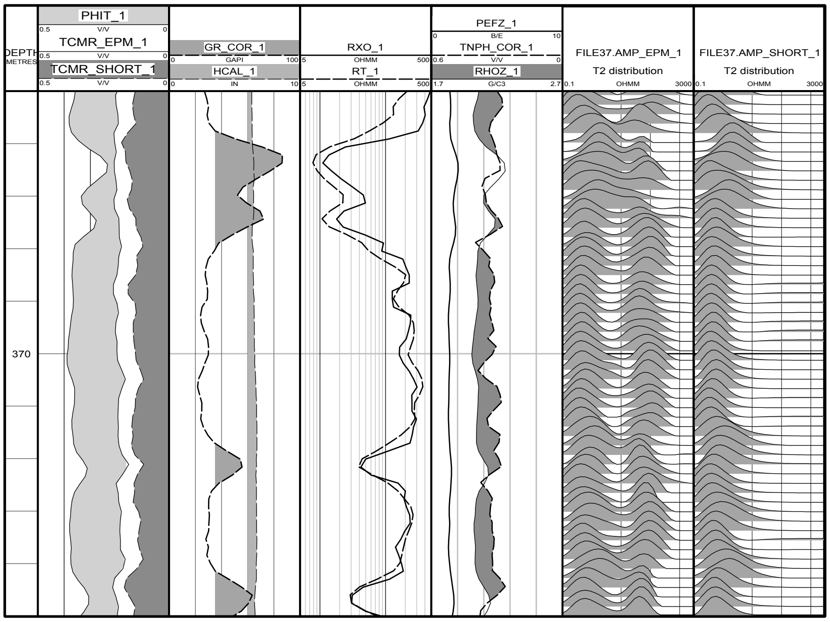

Figure 2: Composite log of the bitumen zone (Schlumberger processing). For clarity, a small depth interval (20 m from 360 down to 380 m) has been plotted. The NMR bimodal distribution is typical of the entire zone; the neutron density is constant over the entire interval. NMR tool: CMR B, speed 120 ft/h, number of echoes: 1200, inter echo time: 0.2 ms, temperature: 13°C, drilling fluid: water based mud.

Processing of Raw CMR Data in the Bitumen Zone

We first re-processed the raw NMR decay signals using the IFP's inversion software MEA. From the DLIS file, we used the Schlumberger DLIS to ASCII conversion toolbox to extract the real and imaginary (R and X) channels that are required as input to the MEA software. The raw signals were converted into porosity units by using the tool's calibration coefficient. We focused on one pass for which the EPM mode was activated (McKeon, 1999). This mode is very useful for detecting short relaxation times. The raw data contain a long and a short echo train and they were analyzed separately instead of combining both signals as proposed by Mc Keon [2]. In the analysis presented below, we do not introduce any hydrogen index correction. These aspects will be considered later.

The analysis of the long echo train is shown in Figure 3. Clear bimodal distributions are found, similar to the results obtained from the analysis shown in Figure 2, and this signature was found to be very uniform over the entire bitumen zone. The bitumen peak lies between 0.3 and 3 ms, while the water peak lies between 40 and 80 ms. The water represents about 50 % of the total estimated porosity (Figure 3, right panel) when taking a cut-off positioned at 4 ms.

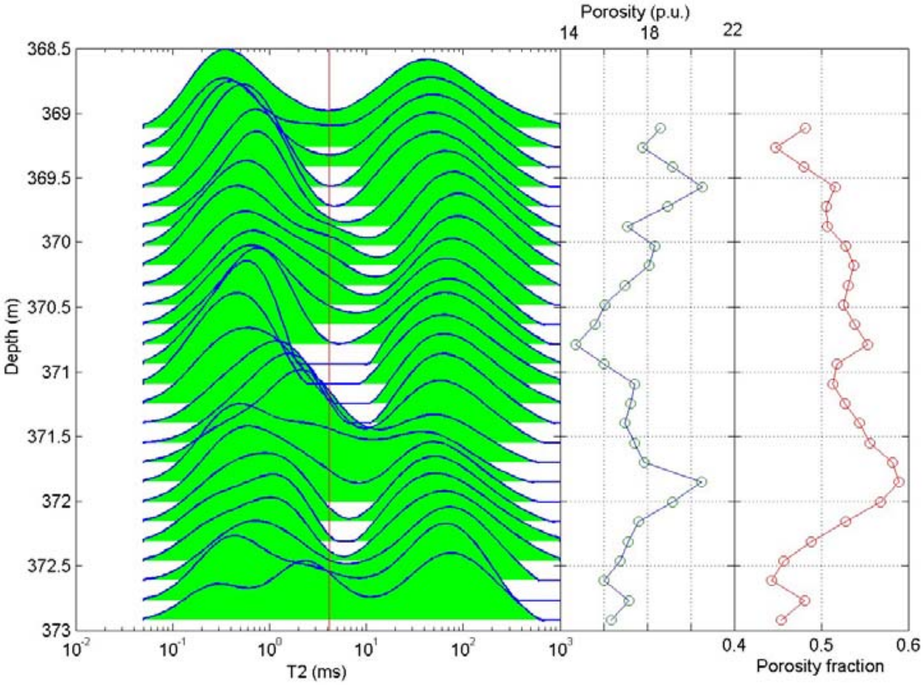

Figure 3: Relaxation time distributions calculated in the bitumen zone around the sample depth (CMR B data using long echo train only, MEA processing). The right panel indicates the fraction of porosity at the left of the vertical line in the left panel.

The analysis of the short echo train is shown in Figure 4. These signals consist in a decay of 30 echoes stacked 10 times, therefore increasing significantly the signal to noise ratio for the short components [2]. In the present case, the SNR calculated by the MEA software increased from 9 up to 25, without loss of vertical resolution. However, relaxation components larger than 10 ms are not available, and a polarization correction should be applied to the components smaller than 10 ms. The analysis presented in Figure 4 includes a polarization correction based on the measurement of T_1 (see Laboratory Measurement section, $T_1/T_2=27$ yielding a correction factor of about 1.09). When comparing Figure 3 and Figure 4 for $T_2<10$ ms we can observe a better resolution of the bitumen peak (its position fluctuates less and is always smaller than 1 ms) and some artifacts in the distribution due to noise are removed. The estimation of porosity is more accurate due to the higher SNR if we consider only the bitumen peak: from Figure 3, the porosity associated with bitumen is about 8.5 p.u., (half of the total porosity of 17 p.u.), whereas the new estimation using the short echo trains is about 10.6 p.u. (considering the depth interval [371 – 371.5] only and excluding the small water contribution, that is 12.5*0.85). Further discussions about the short echo trains are presented in the section Comparison of Laboratory and Log Data.

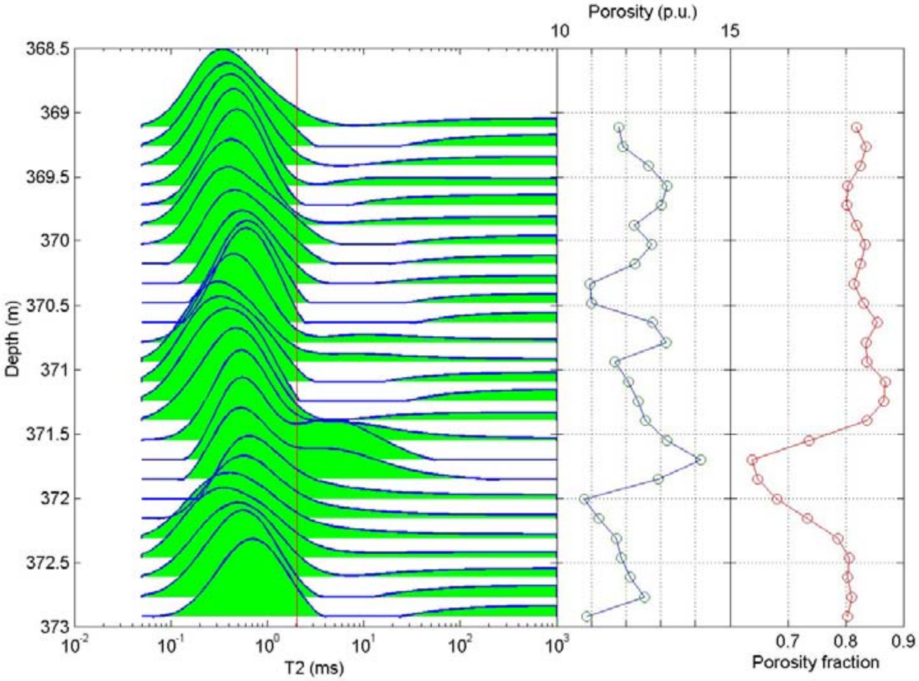

Figure 4: Relaxation time distributions calculated in the bitumen zone around the sample depth. Same pass as in Figure 3, but using CMR B short echo train only, MEA processing. Relaxation times below 10 ms are better resolved (e.g. there is a clear indication of the presence of clays at 371.5). Above 10 ms, they cannot be obtained.

LABORATORY MEASUREMENTS

Two preserved bitumen sand samples were provided for laboratory measurements. During transportation, the samples were kept at a low temperature (below freezing point). Near reservoir temperature (13°C), the samples can be manipulated easily but with caution. From visual examination for both samples, the sand grains can clearly be distinguished, indicating that the bitumen is not wetting the grains. Although relatively surprising, such a behavior has also been observed in other situations [3]. The fact that the sand grains can easily be cleaned when extracting the bitumen with solvent also confirms a water-wet state. The X-ray CT scans clearly indicate a network of micro-fractures that may have various origins (coring, sample handling at low temperature during transportation, etc). The sample also contains denser regions that are visually apparent, corresponding to solid bitumen fractions. In the analysis presented below, the MEA software was also used to analyze laboratory data.

Measurements of Porosity and Saturation

We determined the porosity and the amount of water in the sample by simply varying the temperature, therefore taking advantage of the different temperature dependence of the bitumen and water. At low temperature, the bitumen signature should be shifted to small relaxation values, whereas at high temperature, the bitumen signature is shifted to higher relaxation value as the viscosity is decreasing. For water at the surface of the sand grains, a similar temperature dependence is expected [4], but with much less amplitude.

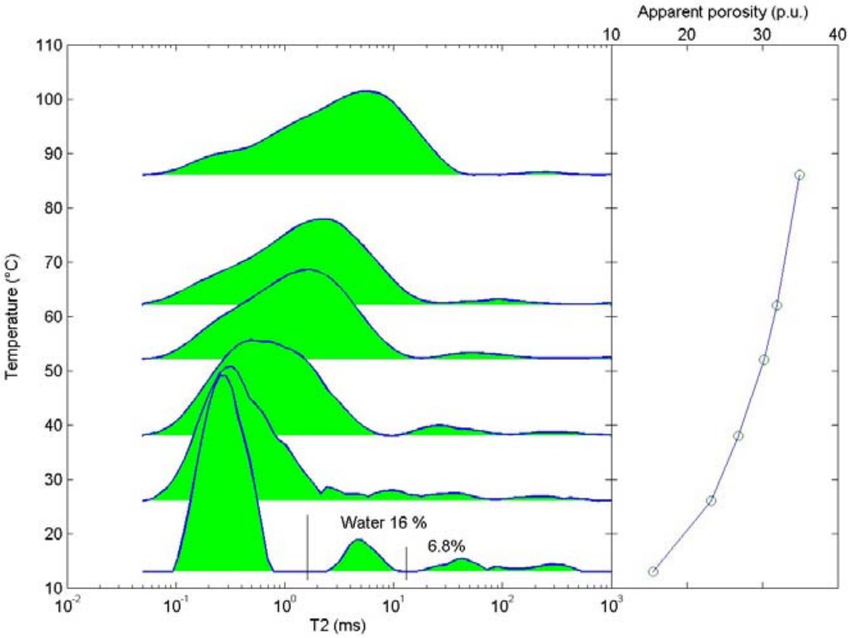

Figure 5: Relaxation time distributions measured as a function of temperature (reservoir temperature 13, 26, 38, 52, 63 and 86°C). The apparent porosity is corrected for temperature, cell signal and includes a hydrogen index of 0.91.

The T_2 distribution of sample 37128 was measured as a function of temperature, from the reservoir temperature of 13°C up to 86°C. The NMR apparatus used is a Maran 2 Ultra (Resonance Instrument Ltd) with a proton Larmor frequency of 2.2 MHz (the CMR resonance frequency is about 2 MHz). The sample (without sleeve) is put in a special cell described elsewhere [4] in which a (non-hydrogen) liquid is circulating to control and stabilize the temperature. The empty cell has a weak signal depending on temperature (5.4% and 12.1% of the sample magnetization at 13°C and 86 °C respectively, in the range $T2<1$ms) which has been measured and subtracted from the measurements before processing the distributions. For each temperature step, the NMR measurement is performed after a minimum of 3 hours to allow the stabilization of temperature, according to the calibration curve. For all measurements, the signal to noise ratio is between 130 and 220. The inter-echo time was 0.160 ms for all measurements.

Results are shown in Figure 5. The base line of the distribution indicates the temperature (13, 26, 38, 52, 62 and 86°C) and the amplitudes are normalized by the porosity (i.e. the surface area under the curve) scaled by an arbitrary factor controlling the visual aspect of the plot. The numbers indicate the fraction of the apparent porosity deduced from partial integration of the distributions. We make the following interpretations:

- At 13°C (reservoir temperature), the three peaks are respectively the signature of bitumen ($T_2<1$ ms), clays ($1<T_2<10$ ms), and water at the sand grain surface

($10<T_2<1000$ ms). The porosity is underestimated because some bitumen components are solid and cannot be detected. Note that the limit of detection of short relaxation times on our laboratory apparatus is nearly the same as for the CMR tool (about 0.2 ms). For the second sample at that temperature, the T_2 distribution was quasi-identical,

- At 86 °C, the bitumen distribution is larger and extend up to 30 ms, overlapping the clay signal. A wide and multi-modal distribution of relaxation times is expected for heavy oils containing a wide range of hydrocarbon chains. The apparent porosity gradually stabilizes indicating that nearly all bitumen components are detected at that temperature (note that the bitumen did not flow at 86°C and that the sample was not damaged).

Between 13°C and 86°C, there is a gradual shift of the bitumen peak along with a widening of the distribution due to the decrease of viscosity, as expected.

Calculation of Porosity and Saturation

The NMR signals are first translated into volumes using a calibration coefficient C determined with water and the apparent hydrogen index (HI) of the liquid saturating the porous media. Then, the porosity can be deduced from the total sample volume.

First, all the magnetization measurements were corrected for temperature using a Curie law (not to confuse with the variation of static magnetic field induced by temperature valid for a logging tool):

$$M_C = M_0(T)\left(\frac{273+T}{273+T_{ref}}\right) \tag{1}$$

where M_0 is the measured magnetization per unit scan (a.u./scan), T is the sample's temperature and T_{ref} is the reference temperature (°C) at which the calibration is performed.

Then, the apparent porosity is deduced from the (corrected) extrapolated magnetization amplitude at t=0 according to:

$$\Phi = M_C \frac{1}{C}\frac{1}{HI}\frac{100}{V_T} \tag{2}$$

where M_C is the measured corrected magnetization per unit scan (a.u./scan), C is the instrument's calibration coefficient (47 a.u./cc/scan) at 26°C, HI is the hydrogen index of the saturating liquid and V_T is the total sample volume (from length and diametre). The above equation has been used to calculate the porosity shown in Figure 5. It assumes that all liquids in the sample have a unique hydrogen index (which is not exact, see below for details). When taking the measured apparent hydrogen index of the bitumen at 86°C (0.91, see Appendix), we obtain a porosity of 15.9, 23.9, 27.6, 31.1, 32.8 and 35.8 p.u. at 13, 26, 38, 52, 63, 86°C respectively. The saturation can be deduced from the distributions measured at 13°C at which the bitumen and water signals are not overlapping, and the distribution measured at 86°C at which the total liquid volume can be calculated precisely. From the 13°C distribution, the magnetization associated with water and the water volume present in the sample is:

$$M_C^w = M_C(T = 13°C)\ fw \quad \text{and} \quad V_w = M_C^w / C = 1.5\ cc \tag{3}$$

where fw = 16 % is the sum of T_2 amplitudes associated with water at 13 °C and M_C the measured corrected total magnetization at 13°C (436 a.u./scan). At 86°C, the corrected magnetization associated with water is subtracted from the total corrected magnetization (981 a.u./scan) and the bitumen volume is deduced from:

$$V_{bit} = \left[M_C(T = 86°C) - M_C^w\right] / C / HI = 21.3\ cc \tag{4}$$

Finally, a porosity and a water saturation estimate can be made:

$$\Phi = \frac{V_{bit} + V_w}{V_T} x100 = 35.6\ p.u. \quad S_w = \frac{V_w}{V_{bit} + V_w} = 6.6\ \% \tag{5}$$

The water saturation indicated above includes the clay bound water. Note that the estimate of saturation is independent of the measurement of total volume (and porosity) and that the volumes indicated are valid at 26°C. The calculations strongly depend on the HI value which has to be measured at the sample temperature (i.e. the HI does not need to be the true HI of the bitumen).

The porosity can also be calculated directly from the weight measurements according to:

$$\rho_s = \Phi\rho_L + (1 - \Phi)\rho_G \Leftrightarrow \Phi = \frac{\rho_G - \rho_s}{\rho_G - \rho_L} \tag{6}$$

where : ρ_S is the measured (apparent) sample density (weight/total volume)
ρ_G is the grain density of the sand (assumed to be 2.65)
ρ_L is the density of the saturating 'liquid' (1.013)

Because the bitumen is very heavy with a density close to water, this simple calculation gives an estimation of porosity quasi-independently of saturation. However, it assumes implicitly that there is no air trapped in the sample, which is obviously not the case when observing the CT scan images. We obtain an overestimated value of 43 %. (Table 1).

Table 1: Porosity from weight measurement, according to Eq. 6. The bitumen has a density of 1013 kg/m^3 and is rated 8° API .

Sample	37128	37133
Sample depth (m)	371.28	371.33
Length / diameter (mm)	55 / 38.5	57 / 38.5
Mass (gr)	124.057	130.217
NMR porosity	35.6	-
NMR/weight porosity	37.4	-
Weight porosity (p.u.)	43.5	42.1

When combining NMR and weight measurements, we avoid the errors induced by the presence of air trapped in the sample and the errors induced by the measurements of length and diameter. The porosity is deduced from:

$$\Phi = \frac{V_{bit} + V_w}{V_{bit} + V_w + V_s} \tag{7}$$

where V_{bit}, V_w and V_g are respectively the bitumen, water and solid volumes. We assume that the solid volume is due to the sand grains of density ρ_G=2.65. From the measurement of the sample weight M_T, we deduce the porosity according to:

$$\Phi = \frac{1}{1 + \frac{M_T - M_L}{\rho_G (V_{bit} + V_w)}} \quad \text{and} \quad M_L = \rho_{bit} V_{bit} + \rho_w V_w \tag{8}$$

where M_L is the mass of liquid in the sample deduced from the NMR measured bitumen and water volumes and the known density. We obtain 37.4 %, which is interpreted as the porosity of the compacted sample.

T_1 Measurements and CMR Short Echo Train Laboratory Simulation

T_1 measurements are useful to make log polarization correction. For bitumen and heavy oils, the T_1/T_2 ratio is not expected to follow usual laws valid for non-viscous liquids ($T_1/T_2 \approx 1$) or liquids in interaction with a solid surface ($T_1/T_2 \approx 2$). In the case of highly viscous liquids, a solid like behavior outside the extreme narrowing regime is expected [5], that is $T_1/T_2 >> 1$. The T_1 distribution measured at 13°C indicate a peak relaxation time located at about 8 ms. We deduce an effective T_1/T_2 ratio at reservoir temperature (13°C):

$$\frac{T_1}{T_2} = \frac{8}{0.3} = 27 \tag{9}$$

In the case of the short echo trains, the impact on the logging data can be easily be estimated. For the short echo trains, the magnetization decrease due to unperfect polarization is then:

$$1 - \exp\left(\frac{-t}{T_1}\right) = 0.92 \quad \text{where t=20 ms} \tag{10}$$

We tested experimentally this polarization decrease by performing the following sequence of measurements on sample 37133:

- measure the reference magnetization using 200 CPMG stacked sequences repeated every 1 s (TE=0.2 ms)
- apply 2 dummy CPMG sequences, then acquire and stack 20 CPMG sequences repeated every 20 ms, which is a simulation of the EPM mode on the CMR B tool.

From these tests, we observed that the magnetization is reduced by a factor 0.94, which is in agreement with the predicted decrease in 10.

COMPARISON OF LOG AND LABORATORY DATA

At reservoir temperature, both the laboratory and logging tools are making poor estimates of the amount of bitumen (Table 2). This is expected because some bitumen components behave like a solid and cannot be detected. As a consequence, the NMR total porosity is severely underestimated. However, the bitumen signature from the log and the laboratory (Figure 6) are very close and essentially influenced by the signal to noise ratio (SNR). Using the short echo train (high SNR), the short relaxation times are better resolved than in the case of the long echo train and are shifted to lower values, closer to the laboratory signature (Figure 6, left panel). Such an effect can be easily be reproduced using simulated echo trains at low SNR. Indeed, taking as input the T_2 distribution measured at the laboratory at SNR=220, we generated synthetic echo trains at SNR=9 or 25 and observe a shift of the peak relaxation time. Statistically speaking, the porosity estimates decreased by 43%. This is also qualitatively indicated in Figure 6 (right panel). The curvature at small time (<2 ms) is less pronounced when SNR is small (long echo train). For the short echo train, the high signal quality allows a much better estimate of the slope, very close to the laboratory measurements. Therefore, there is no ambiguity in identifying the bitumen peak. Using the short echo trains, one can also separate the clay bound water and the bitumen.

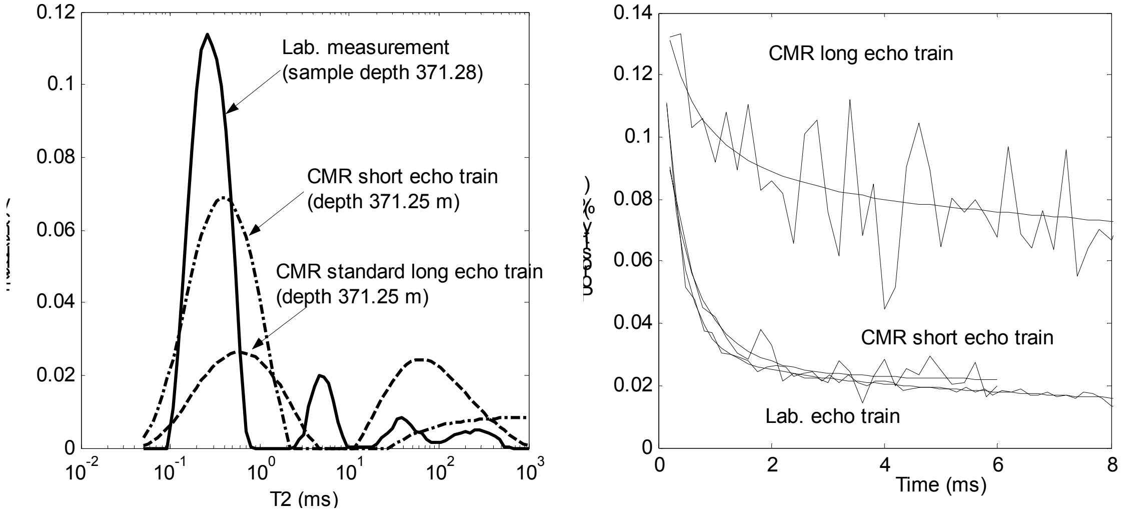

Figure 6: Left panel: comparison of the T_2 distributions measured in the laboratory (sample 37128 at depth 371.28 m) and the log measurement at a similar depth (extracted from Figure 3). Right panel: corresponding raw and fitted echo trains.

The water saturation calculated from the porosity deficit between NMR and density-neutron porosity (24%, Table 2), excluding the bitumen peak, is very different from the laboratory measurement (6.6%). Expressed in terms of porosity units, the amount of water estimated from the log is in excess of 6 p.u. compared to the laboratory measurements. Further studies are needed to explain this discrepancy and none of the following considerations are fully satisfying: (i) a displacement of the bitumen by the mud during or after drilling appears to be difficult (ii) a reading of the CMR tool in the mud cake is unlikely because the hole is of good quality and the depth of investigation of the CMR tool is large enough (2.8 cm).

This study also indicates that the correction of the bitumen peak using an effective hydrogen index (HI) must be performed with caution because such a correction depends on SNR, temperature and inter-echo spacing (TE). From the laboratory measurement, we can calculate an effective HI of 0.39 at 13°C and high SNR and TE=0.16 ms. For the log data considered in this study, the effective hydrogen index is about 0.37 for the short echo train (TE=0.2ms), and 0.29 for the long echo train (TE=0.2ms, without stacking).

Table 2: Summary of the different estimations of water and bitumen at the depth 371.25 m. The numbers do not include any hydrogen index correction unless specified. (*) using the water amount in the long echo train measurement (8.5 p.u.). (**) from the density-neutron porosity (35 p.u.) and the water amount (8.5 p.u.)

	Water (p.u.)	Bitumen (p.u.)	Total porosity (p.u.)	Water saturation (%)
CMR Log Long echo train	8.5	8.5	17	24 (**)
CMR Log Short echo train	-	10.6	19.1 (*)	-
Laboratory at reservoir temp.	2.5	12.0	14.5	
Laboratory at elevated temp.	2.5	31.8 34.9 (HI=0.91)	37.4 (HI=0.91)	6.6

CONCLUSION

We analyzed raw NMR log data in a bitumen zone and compared the results with measurements performed on a preserved sample. At the reservoir temperature, the laboratory and log measurements strongly underestimate the porosity due undetected quasi-solid components in the bitumen. In the laboratory, a simple method allows the estimation of saturation and porosity: at low temperature, we determine the amount of water because there is no overlap of the water and bitumen signals; at elevated temperature, we determine the total amount of liquid in the sample using a measured effective bitumen hydrogen index. The porosity determined by this method is in agreement with the log density-neutron value.

From the comparison of NMR log and laboratory data, we conclude the following:

- the bitumen signature measured in the well and the laboratory are totally coherent and the observed differences are due to the different signal to noise ratio,
- the water saturation for the log and the laboratory disagree and further studies are needed to explain the excess of water in the log measurement,
- the bitumen effective hydrogen index depends on temperature, signal to noise ratio and inter-echo spacing.

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APPENDIX : HYDROGEN INDEX MEASUREMENTS

The hydrogen index HI is defined as the ratio of the number of hydrogen nuclei in the liquid considered to the number of hydrogen nuclei of pure water in the same volume at the same pressure and temperature. In practice, HI is deduced from the measurements of the bitumen magnetization divided the pure water magnetization, per unit volume. Both signals have to be measured with identical acquisition parameters (gain, filter, etc). We used the following procedure:

- measure the NMR magnetization for a known (measured) bitumen mass at 86°C
- calculate the corresponding bitumen volume according to (Butler, 1999):

$$\rho_{bit}(T) = \rho_{bit}(T = 13°C)\left[1 - 0.0603\frac{(T-13)}{100}\right] \tag{11}$$

- measure the NMR magnetization for a known water mass at 86°C
- calculate the corresponding volume according to:

$$\rho_w(T) = 1001.7 - 0.1616T - 0.00262T^2 \quad [\mathrm{kg/m^3}]\ ,\ 10 < T < 290°C \tag{12}$$

At 86°C, the bitumen density is 0.9684 and the water density is 0.9684 (same value). We used a bitumen sample from the separator to determine the bitumen hydrogen index. Using 4.873 g of bitumen and 5.000 g of pure water in a glass container heated at 86°C, we obtain HI=0.906. The echo spacing was 160 µs. Note that the curve given by Kleinberg and Vinegar [6] predict apparent HI value that are much lower because of very different measurement conditions. It is also instructive to compare the HI value obtained by mixing the bitumen with toluene to decrease the bitumen's viscosity and try to catch all relaxation components. We found HI=0.968. Clearly, the HI value measured at 86°C is underestimated but the calculation of volumes will be exact (within instrument's accuracy) because the HI measurement is later used in the same conditions.