Processing of Multi-Acquisition NMR Data

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Summary

Crucial issues in formation evaluation are the determination of porosity, permeability, hydrocarbon volumes, and net-to-gross ratio. Nuclear magnetic resonance (NMR) logging provides measurements that are directly related to these parameters. The NMR response of fluids contained in pores is governed by their T_2- and T_1-relaxation times, diffusion coefficient, and whether or not they wet the rock. In the case where fluids possess a sufficiently large contrast in these properties and NMR data have been acquired with suitably chosen acquisition parameters (i.e., wait times and/or inter-echo times) a separation of water, oil, and gas NMR responses can be made. From these separate NMR responses the hydrocarbon volumes, porosity, and permeability estimates are subsequently calculated. Key in these applications is the ability to include all the acquired log NMR data into the processing towards the desired end result.

Methods exist to derive hydrocarbon volumes from T_2 distributions or from echo decay data. However, these are all methods in which the difference between just two acquisitions that only differ in either wait time or inter-echo time are considered. Over the past years we have developed, tested, and employed an alternative processing technique named multi-acquisition NMR (MacNMR). MacNMR takes any number of log acquisitions (wait time and/or inter-echo time variations) and simultaneously inverts them using a rigorous forward model to derive the desired water and hydrocarbon T_2 distributions. In this paper, we discuss the concepts of MacNMR and demonstrate its versatility in NMR log processing. An example will illustrate its benefits.

Introduction

This paper discusses the method used by Shell to process multi-acquisition nuclear magnetic resonance (NMR) data. The objective of the processing is to extract fluid volumes and properties from multi-acquisition NMR data.

The potential of multi-acquisition NMR logging for water, oil, and gas discrimination and volume quantification was recognized already in 1993. At that time no commercial processing of such data was available. It was decided to develop an in-house multi-acquisition processing capability. From 1993 to 1996 the development effort was focused on the evaluation of potential processing concepts and the development of the necessary mathematical algorithms. In 1996 the actual software implementation was developed, and in October 1996 first results were available and published internally. In March 1997 a company-wide beta test of the software was organized. In August 1997 the software was released company wide and has been in use since then.

Multi-Acquisition Data Processing Methods

As an introduction, we briefly review methods for quantitative processing of multi-acquisition NMR data that are described in the open literature. We make the distinction between methods that operate in the relaxation time domain vs. methods that operate in the acquisition time domain.

Analysis in the Relaxation Time (or T_2) Domain. Here, methods are discussed that operate in the T_2 domain.

Differential Spectrum Method. The differential spectrum method, first published by Akkurt and Vinegar[1] works on dual-

wait-time data. The concept is to independently T_2 invert the long- and short-wait-time echo-decay vectors into a T_2 spectrum. The two resulting T_2 spectra are subtracted and, provided the wait times have been selected suitably,[2] the difference between the two T_2 spectra only arises from fluids with long T_1 components (usually hydrocarbons). Volumes are quantified by integrating the difference T_2 spectrum and correcting for the polarization difference between long and short wait time.

Enhanced Diffusion Method. The enhanced diffusion method, recently published by Akkurt *et al.*,[3] exploits the diffusion contrast between the diffusive brine and the less diffusive (medium-to-heavy) oil (i.e., water diffusion is faster than oil diffusion). The idea is that the inter-echo time is chosen sufficiently long such that the water and oil signals are fully separated in the T_2 domain (i.e., water is at lower T_2 than oil). Determining oil volumes is then just a matter of integrating over the appropriate T_2 range in the T_2 spectrum.

Analysis in the Acquisition Time Domain. Here, methods are discussed that operate in the acquisition time domain.

Time-Domain Analysis. The time-domain analysis method (TDA) operates on dual-wait-time data. This method was first published by Prammer *et al.*[4] The concept is to subtract the measured long- and short-wait-time decay vectors into an echo difference. In case the wait times have been chosen suitably[2] the difference of the two decay vectors should be arising from a long T_1 component (usually a hydrocarbon). This difference echo vector is subsequently T_2 inverted (using ''matched filters,'' which basically means that a uni- or bi-exponential is fitted to the data). In that way, only the T_2 component arising from the hydrocarbon is found. The hydrocarbon volume is deduced by correcting the resulting signal strength from the difference in polarization between long and short wait time.

Echo Ratio Method. This method, published by Flaum *et al.*,[5] works on dual-inter-echo-time data. The long- and short-inter-echo-time echo decays are divided and an apparent diffusion coefficient is calculated. The apparent diffusion coefficient can be used as a qualitative indicator for the presence of gas.

MacNMR Method

MacNMR uses a method that is radically different from the other processing schemes and is a comprehensive implementation of earlier concepts.[1,6] MacNMR employs a forward model to model the measured echo-decay vectors. The starting points in the forward model are the T_2 spectra for each of the fluids present (water, oil, and/or gas) that would be measured at infinite wait time and zero gradient. From these T_2 spectra, echo-decay vectors are constructed by accounting for the effects of hydrogen index, polarization, and diffusion. The best-fit T_2 spectra are found by inverting the forward model to the measured echo-decay vectors.

All measured echo-decay vectors included in the inversion are treated on an equal statistical footing. They are weighted with their respective rms-noise values. Hence, decays with the lowest noise contribute most. In principle, any number of echo-decay vectors can be included in the inversion. The current software implementation of MacNMR accepts up to a maximum of six echo-decay vectors, totaling a maximum of 7,000 echoes. The inversion typically takes less than 1 second per depth increment.

In a sense, MacNMR employs a very classical concept in that it defines unknown variables (T_2 spectra for the fluids present) that are determined from the available data (i.e., all the acquired decay vectors) by error minimization. Between the unknown variables and the data is a forward model. The forward model contains the effects of inter-echo-time variation and wait-time variation.
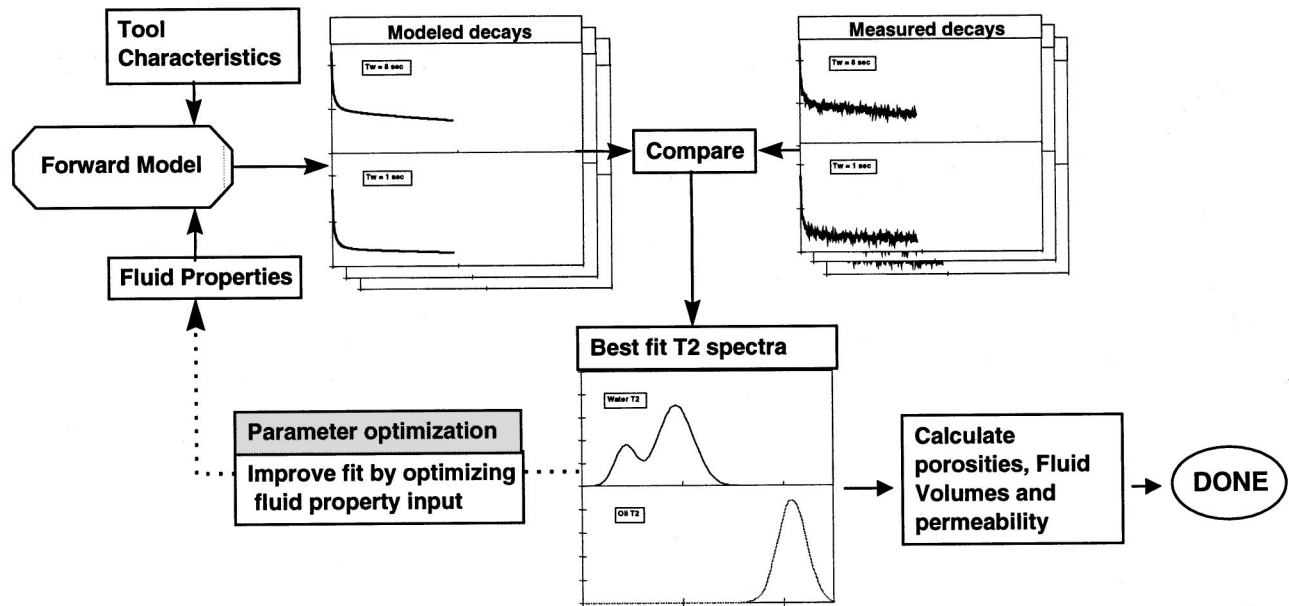
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Fig. 1–Schematic of the MacNMR forward model inversion approach.

The Forward Model

In multi-acquisition NMR there are two parameters that can be varied: wait time and inter-echo time. Depending on wait time and inter-echo time a certain echo-decay vector is measured. The wait time determines the polarization of the fluid and the inter-echo time determines the diffusion decay of the fluid as given by the following expression:

$$M(t_j, T_w, T_e) = \sum_{f=o,w,g} \sum_{i=1}^{n} H_f P_f(T_w) d_f(t_j, T_e) A_{fi} e^{-t_j/T_{2i}}, \quad (1)$$

in which $M(t_j)$ is the measured echo amplitude at time t_j, and n is the number of array elements in the T_2 spectrum. Hydrogen index H_f, polarization P_f, and diffusion decay d_f, are calculated from input parameters such as T_1 and diffusion constants of the fluids. The desired water, oil, and gas T_2 spectra that are to be found from inversion from the measured input echo-decay vectors $M(t)$ are represented by A_{fi}. The forward model accounts for the effects of hydrogen index, finite wait time, and chosen inter-echo time. Hence, the desired T_2 spectra (A_{fi}) are those that would be measured at infinite wait time and zero gradient (homogeneous magnetic field) and represent true NMR porosity.

Next, we will describe the elements of the forward model.

Hydrogen Index. Hydrogen index is a fluid property independent of wait and inter-echo time. By definition, fresh water has a hydrogen index equal to unity at room temperature. Saline water and oils have a hydrogen index that is close to unity. The hydrogen index of gas depends mainly on composition, temperature, and pressure.[7]

Polarization. Polarization of a fluid in a pore is dependent on its T_1 and the applied wait time T_w according to[1]

$$P_f = 1 - e^{-T_w/T_{1f}}. \quad (2)$$

In case the fluid is nonwetting, T_{1f} is equal to its bulk T_1. In case the fluid is wetting, the T_1 is a distribution, which can be estimated from the T_2 distribution. In principle, any relationship between T_1 and T_2 can be implemented. Currently, we use the simplest form of a constant ratio:

$$T_{1i} = R T_{2i}. \quad (3)$$

Ratio R is typically between 1 and 3 for water-wet sandstones.[8] Using this ratio R, a T_1 spectrum for a wetting fluid is now obtained and Eq. 2 can be evaluated.

Diffusion Decay. In a gradient field an additional decay arises due to molecular diffusion within the sensed volume. For a fixed gradient this additional decay is described by the following expression:[1,6]

$$d_f(t) = e^{-D_f \gamma^2 G^2 T_e^2 t/12}, \quad (4)$$

in which D_f is the diffusion constant of the fluid, γ the gyromagnetic ratio of hydrogen, G the prevailing magnetic-field gradient, and T_e the inter-echo time. If a field gradient distribution is present [as with combinable magnetic resonance (CMR)], then

$$d_f(t) = \int_G P(G) e^{-D_f \gamma^2 G^2 T_e^2 t/12} dG, \quad (5)$$

in which $P(G)$ is the tool gradient distribution as experienced by the fluid. For completeness, it is mentioned that field inhomogeneities in the rock due to magnetic susceptibility contrasts are ignored. This is not necessarily a justifiable assumption. At the operating frequency of the NMR tools internal gradients may be as large as the external gradient in some rocks. In any case, an effective gradient (if known) can be used in the forward model evaluation.

The fluid diffusion constant D_f does not necessarily have to be the bulk diffusion constant. In the case where diffusion is restricted, the restricted diffusion constant can be fed into Eq. 4 or 5. In our current implementation, the dependence of the restricted diffusion constant on inter-echo time is ignored and, hence, an effective restricted diffusion constant is used. This appears to be sufficiently accurate with the present data quality.

However, the MacNMR concept allows modeling of both effects to be included if needed.

Inversion of the Forward Model. With the forward model available to describe the measured decay vectors, the inversion process is nothing more than finding the A_{fi} (T_2 spectra for fluids present) that best fit the measured echo-decay vectors. **Fig. 1** shows a schematic of the MacNMR forward model inversion approach. The described forward model is linear and MacNMR finds the best-fit T_2 spectra from regression.

In the inversion process a zeroth-order regularization term is included. The strength of the regularization term is determined by the weighted mean of the individual signal-to-noise (S/N) ratios of the input echo-decay vectors.
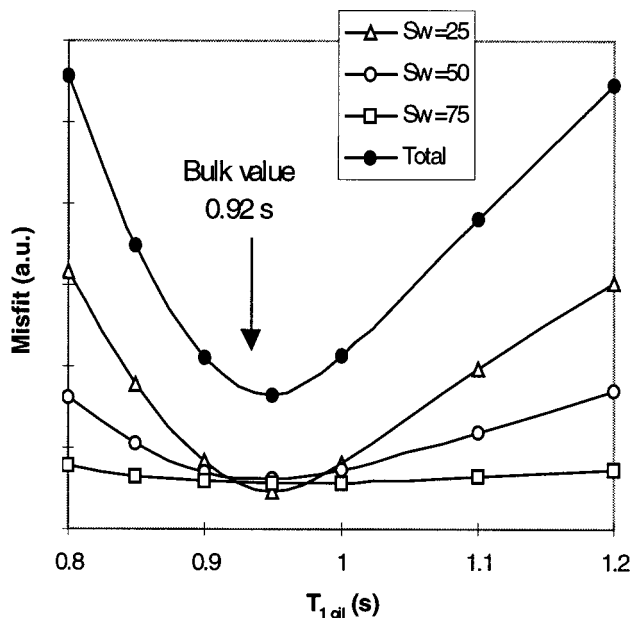
Fig. 2—Rms misfit vs. T1 of the oil. The minimum in rms at T_{1oil} of 0.95 represents the best-fit T_{1oil} value. This is to be compared with the measured bulk T_{1oil} value of this oil of 0.92 s. The curve labeled Total is the sum of the misfits for the S_w =25 to S_w=75 cases.

Fig. 3—Rms misfit vs. diffusion constant of the oil. The minimum in rms at D_{oil} of 7×10^{-9} m^2/s represents the best-fit D_{oil} value found from the NMR log data.

In the inversion process each input echo-decay vector is weighted with its rms-noise value. Hence, every echo-decay vector contributes equally in a statistical sense to the obtained solution.

Fluid Properties From the Log Data. Input to the forward model are the fluid properties (i.e., diffusion constants, T_1, and ratio T_1/T_2). If the fluids are known, these may be obtained from correlations.[7] Unfortunately, fluids are often not known or only very approximately. MacNMR offers the possibility to derive fluid properties from the NMR log data. After inversion, the remaining misfit to the measured decays is calculated. That misfit should be small if all the input parameters are correct. Hence, the misfit can be minimized by optimizing a certain input fluid property. Effectively, optimizing the fluid property is becoming part of the data-fitting process. In our current implementation, the user manually varies the fluid properties, but in principle, an automatic search can be used. Clearly, such error minimization is only successful if the available log data carry sufficient information on the desired fluid property. Note that NMR log acquisition programs can be designed such that sensitivity to a certain fluid property is either maximal or minimal.

Fig. 2 demonstrates the MacNMR fluid property determination on a rock sample measured in the laboratory. The same sandstone sample at three different oil saturation was measured at wait times of 0.3, 0.5, 1, 3, and 8 seconds. The value for T_{1oil} is found by minimizing the misfit as described above. A value T_{1oil} of 0.95 s is found which compares very well with the value for T_{1oil} of 0.92 s as measured on a bulk sample of the same fluid. Note that the same T_{1oil} value is found for every saturation and that the sharpest determination is possible at the highest oil saturation. In a similar way, D_{oil} is obtained from measurements at multiple T_e in a gradient field (see **Fig. 3**).

T_2 **Spectra From Forward Model Inversion.** After simultaneous inversion, the T_2 spectra for the fluids are obtained. An important difference between MacNMR and other inversion schemes is that the effects of polarization and diffusion decay are explicitly included in the forward model. MacNMR obtains T_2 spectra that would have been measured at infinite wait time and zero diffusion. The important consequence is that signals do not appear at their apparent T_{2D} but at their T_2. For example, for a
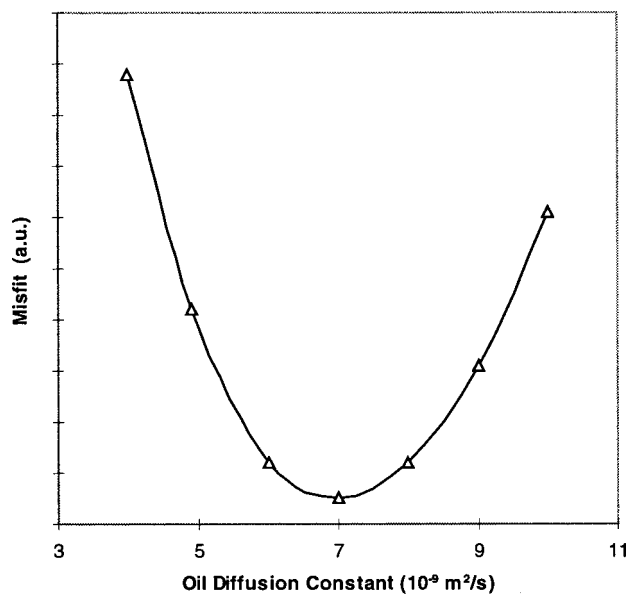
typical gradient of 0.2 T/m [20 G/cm], inter-echo time (1.2 ms) and gas diffusion coefficient (100×10^{-9} m^2/s), gas will decay with a T_{2D} of 29 ms. MacNMR inversion puts gas at its bulk T_2, and T_{2D} is calculated from the input gradients, inter-echo time, and gas diffusion coefficient.

In many cases, it is more desirable to visualize T_2 spectra on a "conventional" scale that has gradient effects. The zero gradient T_2 spectra can be readily transformed to a gradient situation. The transformed T_2 spectra can then be used for plotting and visualization purposes.

In the inversion process constraints can be put on the allowable range of T_2. In the example above one could constrain the gas T_2 spectrum to a narrow range around the expected bulk T_2.

The T_2 spectra derived from the simultaneous inversion are post-processed to yield the desired deliverables: Fluid volumes, porosity, bound and movable fluids, clay bound water, and permeabilities.

Versatility and Qualities of MacNMR. A few features make this processing method very attractive.

It is not just dual-wait time or dual-inter-echo time but both techniques at the same time. Hence, the water-hydrocarbon differentiation capacities of both techniques are combined to yield a more reliable result.

Provided acquisitions are chosen suitably, fluid properties can be extracted from the log data. There is significant benefit in this. Crude oil properties and also oil-based mud-filtrate properties are not easily *a priori* estimated. If incorrect parameters are used incorrect fluid volumes are derived from the NMR log. To get fluid properties from the log data eliminates that uncertainty. (For completeness, it is mentioned that NMR logging acquisition schemes can be designed to minimize the impact of an incorrect fluid property.) Moreover, the log-derived fluid property itself may provide valuable information on the formation fluids [i.e., T_1 and/or D may correlate with the gas-oil ratio (GOR) or condensate-gas ratio]. Using MacNMR fewer acquisitions are required to determine fluid properties compared to other methods.[9]

There is no inherent preference for either wait-time or inter-echo-time acquisitions. Every acquisition is weighted with its rms-noise value and contributes equally in a statistical sense to the obtained solution. This also implies that there is automatic insensitivity to occasional bad or noisy data.

The MRIL total porosity mode of logging generates a separate echo-decay vector of 10 echoes with an inter-echo time of 0.6
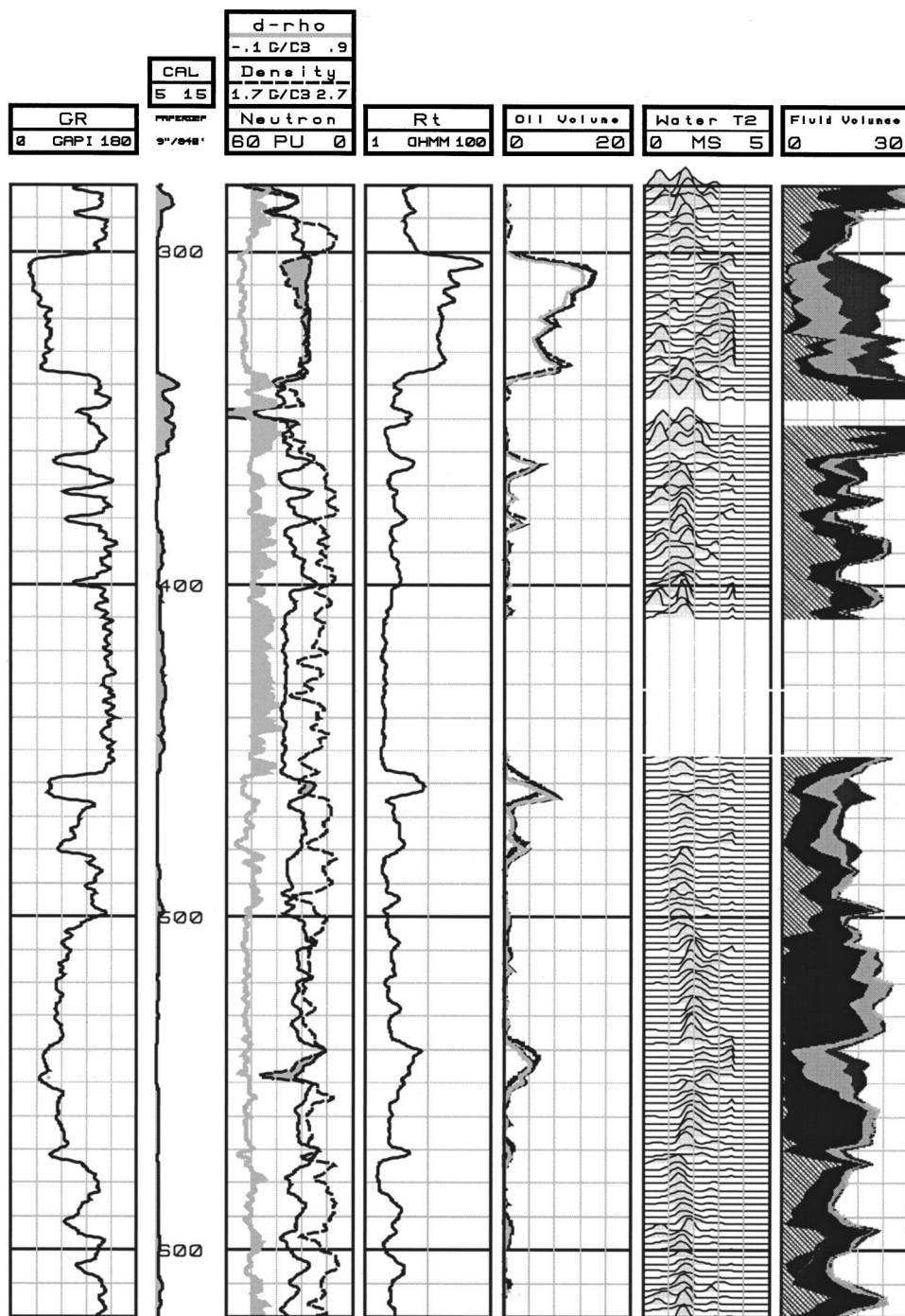
Fig. 4–Example MacNMR evaluation. Track 5 shows the oil volume (i.e., not oil saturation) as found from MacNMR in solid gray when using the estimated fluid properties, in solid black when using the best-fit fluid properties, and with the dashed line when using only the dual-wait-time data. Track 7 shows the fluid volumes in gray coding: hatched is CBW, black is BVI, light gray is free water, and dark gray is oil.

ms.[10] The CMR enhanced precision mode generates a similar short-echo-decay vector (30 to 100 echoes).[11] Both these acquisitions are measured with high S/N and will better resolve the fast T_2 components. MacNMR includes that high-S/N decay vector in its simultaneous inversion just like another acquisition. The advantages of processing such data simultaneously compared to a "slicing" technique has been discussed elsewhere.[12]

There is no need for simplifications or approximations. In other dual-wait-time-processing methods it is (implicitly) assumed that water is fully polarized in short- and long-wait-time acquisitions. If in reality water is underpolarized at the short wait time, then that underpolarized water may be incorrectly interpreted as

hydrocarbon. Underpolarized water may be seen in high-permeable rocks (with large pores and, hence, large T_2) that are at high S_w.

Sensitivity and Limitations of MacNMR. It is not the purpose of the present paper to explore the application envelope of the MacNMR technique. In addition to the points made in the previous section, a few general, qualitative, statements can be readily made. Simultaneous use of all available data leaves less freedom for incorrect interpretation than when a subset is used. It will be obvious that oil and water can be separated only if there is sufficient contrast in at least one NMR parameter, T_1 or D; unfortu-

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nately, no simple rules can be given, as the sensitivities depend on many factors, such as the spectrum of the water-filled rock, bulk fluid properties, noise level and number of echoes, contrast in T_w and in T_e, and field gradient. Generating synthetic data from known answers is a powerful means to analyze the sensitivities in any given situation.

Synthetic NMR Log Data Generation

The forward model described above is also an excellent vehicle for generating synthetic data. Starting from saturation and rock properties (i.e., porosity and permeability) and fluid properties (T_1 and D), the T_2 distributions for water and hydrocarbon can be selected from a database and/or calculated. From these T_2 spectra synthetic echo-decay vectors can be generated for a given wait time, inter-echo, gradient (distribution), and noise level. The ability to generate synthetic log data that can be processed as if real is extremely useful,[13] for example:

• To estimate the impact of noise on the uncertainty in the end deliverable, i.e., porosity, hydrocarbon volume, BVI and capillary pressure curve.[14]

• To investigate the usefulness of a proposed acquisition for the logging objective in the log planning phase.

• Optimization of acquisition parameters for oil and gas volume and property determination.

Example

The example is from a sandstone reservoir containing a light oil. There is poor hole quality in the shale sections. Neutron and density logs do not appear very reliable due to washouts.

Based on the viscosity (0.34 cP) and known pressure (88 bar) and temperature (107°C), the T_1 of the oil is estimated to be 4.5 s and the diffusion constant is estimated to be 4.9×10^{-9} m²/s. The well was drilled with a water-based mud. The well was logged with a 4.5-in. MRIL-C tool (hole size 6 in.) with the objective to determine (among other things) the type and volumes of the fluids in the flushed zone.

A number of acquisitions were gathered in different passes. The following passes were used in data analysis:

• A dual-wait-time pass at an inter-echo time of 0.9 ms with 1- and 8-s wait times (210 echoes).

• A dual-inter-echo-time pass at 1.2 and 2.4 ms inter-echo times and 10-s wait time.

• A pass with a bound fluid acquisition at an inter-echo time of 1.2 ms and 0.8-s wait time and a total porosity acquisition (10 echoes at 0.6-ms inter-echo time with a 0.02-s wait time)

Fig. 4 shows the MacNMR analysis of this dataset together with the conventional logs. Fig. 4 clearly shows the washouts in the shale sections. On the NMR log these sections are recognized from the too high porosity (340 to 360 ft). The fluid volumes resulting from the MacNMR analysis are plotted in Track 7. The track shows the oil to be present in the sand from 300 to 340 ft and also in the thinner sands deeper down. The water-based mud filtrate is visible as free water. (Note that the NMR tools read in the invaded zone, and hence, the derived volumes are valid for the flushed zone.) In the analysis we have included the total porosity acquisition leading to a well-resolved T_2 spectrum at low T_2, and hence, a reliable clay-bound water (CBW) measurement.

As part of the data analysis it was attempted to extract fluid properties. For the set of wait times available it can be shown that there is not a large sensitivity to T_1 of the oil.[2] Vice versa, the resulting oil volume found from the NMR data is insensitive to the exact value of T_1 used. With the availability of the set of inter-echo times there is sensitivity to the diffusion constant of the oil. Optimization for oil diffusion coefficient leads to a value of 7×10^{-9} m²/s, which is slightly larger than expected from viscosity correlations. This appears to be a common observation and is caused by a nonzero GOR of the formation oil.[15] If the 2.4 ms inter-echo time dataset is not included in the optimization then the sensitivity to the oil diffusion constant is significantly reduced.

This is partly due to the fact that with only 210 echoes (at T_e = 1.2 ms) acquired, the higher end of the T_2 scale cannot be resolved.

The resulting oil volume will depend on the value of input parameters used. Track 5 shows the oil volume resulting from three analysis scenarios:

• Using all acquisitions with the estimated fluid properties.

• Using all acquisitions with the best-fit fluid properties.

• Using only the dual-wait-time plus total porosity acquisition with the best-fit fluid properties.

Track 5 shows that the best-fit fluid properties result in slightly higher oil volumes. Once the best-fit properties are found, using only the dual-wait-time plus total porosity data leads to the same result as using all acquisitions. The latter gives confidence that the analysis and results are correct.

Two more examples have been published elsewhere and can be found in Refs. 13 and 16.

Conclusions

The MacNMR methodology described provides inversion of multiple acquisitions by forward modeling. It allows simultaneous use of all data, both with varying wait time and varying inter-echo time. The forward model allows all physical effects to be incorporated without any approximations.

MacNMR is a powerful tool for differentiating water from hydrocarbon, thus providing a water saturation in the flushed zone, and allowing an accurate porosity evaluation in cases of low-hydrogen index, such as gas. Another application is the *in-situ* determination of the NMR parameters (T_1 and D), in order to differentiate gas from oil, or to estimate crude properties.

MacNMR also provides an elegant method to combine total porosity (MRIL) or enhanced precision (CMR) data with a normal acquisition for improved determination of clay-bound water and capillary-bound water.

Nomenclature

M = nuclear magnetization
A_f = partial porosity
t_j = time, s
T_w = wait time, s
T_e = interecho time, s [ms]
T_1 = longitudinal relaxation time, s
T_2 = transverse relaxation time, s
T_{1f} = T_1 of fluid f, s
R = ratio of T_1 and T_2, s
D = molecular diffusion coefficient, m²/s
G = magnetic field gradient, T/m [G/cm]
$P(G)$ = gradient distribution function
P = nuclear spin polarization
d = diffusion decay
S_w = water saturation
γ = gyromagnetic ratio, s^{-1} T^{-1}

Suffices

f = fluid (water, oil, or gas)
i = component of T_1 or T_2 spectrum

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SI Metric Conversion Factors

bar $\times$ 1.0*	E+05	= Pa
cp $\times$ 1.0*	E−03	= Pa·s
ft $\times$ 3.048*	E−01	= m
in. $\times$ 2.54*	E+00	= cm

*Conversion factors are exact. **SPEREE**

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