A NOVEL METHOD TO DETERMINE NMR PETROPHYSICAL PARAMETERS FROM DRILL CUTTINGS

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ABSTRACT

In the past, measuring the NMR petrophysical properties of drill cuttings has been very difficult for two reasons: first, small rock samples yield only a small NMR signal which corresponds to a small signal-to-noise ratio and, second, the procedures for sample preparation and processing did not allow fast enough turn-around time. The combination of these two factors prevented NMR measurement of drill cuttings from becoming a mud logging routine.

We have developed technology to obtain the NMR petrophysical parameters both at the well site and in the laboratory. The instrument uses modern electronics to overcome the signal-to-noise problem and weighs only 25 kg, making it easily portable.

Using our procedures on drill cuttings during mud logging allows us to determine:
- Total and Effective porosity;
- Absolute permeability;
- Irreducible water saturation Swirr.

Most other NMR petrophysical parameters (identifying pay zones, wettability condition etc.) can, in principle, also be derived. They will be the topic of a later paper, as deriving them with short turn around times depends primarily on the NMR measurement skills of the user.

A new model was developed for NMR permeability estimates for multi-saturated cuttings and core plugs from clastic deposits.

Cuttings *larger than 1 mm*, washed from mud with water, are suitable for permeability estimations. Unwashed cuttings (or drilling mud) can be used for preliminary rejection of the rocks with distinctive non-reservoir properties based on the NMR measurements, so long as the drilling mud does not contain oil. Cuttings fractions *larger than 3 mm*, washed from mud with water, are suitable for the evaluation of the reservoir rock and saturating fluids properties. Smaller cuttings (from 1mm to 3 mm) can only be used to evaluate the above parameters if the rock does not contain pores with the filtration radius of $R_f > 20$ μm.

The technology has been successfully applied on a number of artificial models, outcrops and real cutting samples from oil and gas reservoirs in Canada, USA, China and FSU. It offers a low-cost option for log calibration and even an alternative solution when it is difficult to obtain NMR logs from a wireline.

INTRODUCTION

Faster drilling and higher drilling cost (especially offshore) dictate reducing cost and decreasing the time required for well evaluation. Simultaneously, we must guarantee reliability and authenticity of the results. This is especially important for reservoirs with complicated geology and with long exploitation time, since the *in-situ* oil viscosity is usually different in different parts of reservoirs at this stage.

Formation evaluation includes the following methods for different scales:
- Variable well test techniques for direct reservoir rocks' hydro-conductivity evaluation (mega scale);
- Indirect continuous logging measurements (macro scale);
- Direct and indirect laboratory measurements on full-scale cores, core plugs and thin sections (micro scale).

Unfortunately, these methods have the following main disadvantages:
1. At any given time the measurements sample only one part of the well.
2. Characterization of well cross-sections occurs only after finalizing of the drilling process.

The formation evaluation "while-drilling" is a steadily growing area. However, there are

various drawbacks (Santarelli at al., 1998; Geological and Mud Logging in Drilling Control, 1982; Exlog, 1985; Petroleum Engineering Handbook, 1992; Lukianov, 1989).

- The lag time before data is available may be long if the rate of penetration is slow (for memory tools even longer).
- Technologies are relatively expensive and their application requires a high degree of well stability.
- The interpretation of the results includes operational noise from the drilling process.

Trends in new technology include:
- Increased application of LWD technology with on-line information support for tool calibration;
- Optimization of log plan at the well site;
- More complete investigation of core samples by advanced core analysis techniques;
- More complete investigation of cuttings and drilling mud during the drilling process.

While most cuttings investigations are carried out in stationary laboratories (Fens et al., 1998; Tulbovich, 1990; Wothington et al., 1987; Gupta et al., 2000; Mirotchnik et al., 1999; Guzman, 1999; Kantzas et al., 2001; Zamfes, 2000) we are proposing to carry out the analysis in real time.

Recently a number of techniques for quantitative formation characterization using cuttings at the well site were developed and tested (Santarelli, 1998; Worthington et al., 1987; Zamfes, 2000; Marsala et al., 1977; Nes et al, 1998). The major weaknesses of these technologies are:
1. It is difficult to use one type of measurements to determine the generally required petro-physical parameters (porosity and perme-ability), i.e. quantitative determination of filtration-capacity properties (FCP) require a set of different tools (Santarelli, 1998; Marsala et al., 1977; Nes et al, 1998).
2. It takes too long to provide quantitative on-line information during drilling on well site (Santarelli, 1998; Zamfes, 2000).

Advanced techniques on cuttings can be used for the following purposes (Geological and Mud Logging in Drilling Control, 1982; Exlog, 1985; Petroleum Engineering Handbook, 1992; Subert, 1995; Lukianov (1989, 1990)):
- Lithology determination;
- Estimating formation and mineralogical density of rocks;
- Estimating acoustic parameters of rocks;
- Determination of volume percentage of quartz, clay, calcite, dolomite, sulfites etc;
- Grain size analysis for sedimentary rocks;
- Estimating the content of residual oil;
- Determining the open porosity and absolute permeability on fractions with appropriate particle sizes of cuttings (usually more than 3 mm).

Advanced mud logging at the well site is labor intensive and expensive and can mostly be applied to cuttings with particle sizes of more than 3 mm. An automated petrophysical para-meter determination would be most useful.

The NMR method applied to measurements on cuttings has the potential to be one of the most important methods for well site estimation of well and reservoir properties.

The NMR method with high electromagnetic fields was primarily used in the former USSR (State Scientific & Research Institute of Nuclear Geophysics and Geochemistry, 1982). In this modification, NMR was used for porosity determination (POR), evaluation of the irreducible water saturation (Swirr), free fluid index (FFI) estimation and other parameters. All measurements were carried out on the coarse fractions of cuttings. Data processing and interpretation was methodologically identical to NMR data interpretation on core samples. The difficulties of measurements with high field NMR spectrometers (high frequency) and difficulty of handling their large size prevented wider use of this technology at the well site. Attempts to use low field NMR for cuttings investigation by others were reported by Santarelli, 1998. In addition, the processes used on coarse cuttings are not effective for determining the petrophysical parameters on fine and middle size cuttings (Tulbovich, 1990). Several low field NMR relaxometers appeared during past decade (Corespec-1000[TM], Maran-Ultra[TM], Minispec-mq10[TM], MR-ML[TM]). These devices are suited

for wide range of application in laboratory environments on core plugs and cuttings and give results comparable to logging conditions. Some of them (Maran-Ultra™, and MR-ML™) are portable and can be installed at the well site.

Recent progress in Low Field NMR applications brought forward more effective methods for reservoir evaluation. While the work was mostly done for core, similar approaches can be applied for NMR measurements on cuttings.

The developed Low Field NMR technology (MR-ML™), briefly discussed in this paper, addresses the above needs by providing petrophysical parameters of reservoir rocks and saturating fluids. The methodology for its development included:

- A market survey and evaluation of existing NMR laboratory equipment that could be adapted for the scope of the technology resulted in establishing the requirements for the new generation of portable, industrial NMR device (MR-ML™).
- A feasibility study of using drill cuttings as small as 1 mm to 6.35 mm diameter resulted in experimental procedures for the measurements.
- Pilot experiments were carried out on artificially generated cuttings and compared to cores for homogeneous samples and reservoir rock samples from known formations (Berea, Jurassic rocks from Western Siberia Reservoirs, Middle East Carbonates, Western Canadian shaly sandstones from shallow gas wells, etc.) In additions, non-consolidated sand models and samples from artificially made synthetic porous media with very well known properties were evaluated. The procedures for the measurements were verified and NMR measurements on cuttings for reservoir rock characterization were proven. Fine-tuning and integration of all processes and algorithms yielded a "one-button" measurement process. Limits in terms of rock grain size, average pore size, and dimensions of the cuttings, among other considerations, were also established.
- Finally, experimental trial on customers' supplied realistic samples was tested focusing on timing, procedures for cuttings collection etc. These tests verified the robust-ness of the equipment its operation simplicity showing it could be used by a mud-logging operator without specific training in NMR measurements. Tests were carried out domestically (Canada and USA) and overseas (China).

In this paper we address the application of the technology to samples from clastics. While some carbonates have been investigated, more work on them is required. First, we will determine the size of the cutting that can be measured with present instrumentation. Second we will summarize the systematic research carried out to verify that the porosity determination is correct. Last, we will verify the permeability determination.

DETERMINATION OF CUTTING'S PARTICLE SIZE FOR CHARACTERIZATION OF POROUS MEDIA IN CLASTICS

The amount of petrophysical information from cuttings depends on the size of cuttings that are available for measurements. Recent studies on cuttings for acoustic parameters of rocks (Marsala et al., 1977; Nes et al., 1998) demonstrated the ability to use cuttings as small as 1 mm.

Earlier studies were practically limited by determination of NMR porosity (POR_{NMR}) on clastic samples larger than 3 mm (Tulbovich, 1990; Akselrod et al., 1990). They demonstrated that acceptable POR_{NMR} from cuttings could be obtained for petrophysical characterization of hydrocarbon bearing rocks. The work was based on longitudinal relaxation times (T_1 values). NMR spectra determination was performed using uni-, bi- or stretch exponential analysis. The data were applied for total porosity and irreducible water content estimates. Unfortunately, the same characterization of petrophysical parameters of rocks with complicated topology (structure and texture) does not apply. Recent studies demonstrated that complicated structure of porous media in fully saturated clastics ($S_w=100\%$) can be clearly described based on T_1 and T_2 spectra from Low Field NMR relaxometers (Kenyon, 1992; Vinegar, 1995; Coates et al., 1999).

The information from cuttings for STPM (structure and texture of porous media) determination was derived with SEM/BSE

imaging analysis techniques and published elsewhere (Fens et al., 1998). The authors demonstrated that their analysis can be used for porosity (ø) and permeability (PERM) determination on cuttings larger than 3 mm^3 volume. The results are consistent with core plugs. This confirms petrophysical properties determination, but not yet the minimum size for wettability characterization by NMR. It was necessary to verify this independently due to the different physical natures of these two methods (NMR and SEM/BSE image analysis). Different petrophysical models were used for both techniques, respectively. The SEM/BSE image analysis is similar to those used for ø and **PERM** determination on thin sections (VNIGNI, 1978). This method estimates transmissibility of pores. The Kozeny model (Kozeny, 1927) can be used for PERM determination.

NMR spectra are dependent on topology of pores (shape and size) representing major part of pore volume (Coates et al., 1999). The PERM values from rocks with inter-granular porosity are dependent on size of pore throats. Information about cross-sections of pore throats can be recovered from relationship of pore bodies' sizes with pore throats' sizes.

Thus the ø values can be estimated by NMR with errors not higher than with the direct methods. The errors in permeability values estimated using known models (Coates et al., 1999) can be significant as addressed below.

Experimental considerations

Transverse relaxation times (T_2 relaxation curves – RC) measurements were performed on core samples and cuttings of different sizes that were made from the same rocks. Both samples (cores and cuttings) had a water wet pore surface with Sw=100%.

The difference in core samples and drilling cuttings structure with wide pores' cross-sections range becomes more apparent under fully water-saturated conditions. The permeability and effective porosity of rocks with inter-granular porosity are generally dependent on the pores' throats.

The samples with identical filtration capacity properties (FCP) and NMR characteristics were grouped for the measurements.

The following experimental program was carried out for solving above mentioned problem:
1. Rock samples with inter-granular porosity were collected (5 samples from known outcrops and 15 samples from clastic deposits).
2. Total porosity, permeability and irreducible water were determined by direct methods.
3. NMR measurements @ Sw=100% on the samples with different FCP were carried out.
4. T_2 relaxation curves (RC) were processed and spectra calculated.
5. Samples with similar FCP were grouped and used for production of artificial cuttings.
6. Cuttings of different sizes resulted. They were sorted by wet sieving.
7. NMR measurements on cuttings were performed @ Sw=100%.
8. Results of measurements (T_2 – RC) were processed and T_2 spectra delivered.
9. T_2 spectra from plugs and cuttings were compared.
10. The averaged filtration radii (R_{f_i}) for different groups of pores were calculated.

The petrophysical characteristics of samples are presented in Table 1a and 1b.

The differential T_2 spectra from some investigated samples are presented in Figure 1. T_2 cumulative curves are presented in Figure 2. The cumulative curves were used for samples grouping and for calculation of the errors in the spectrum using multi-exponential analysis.

The pore distributions (R_f) affecting fluid flow in samples are in Table 2. A correlation of transverse relaxation times (T_2) with size of pore nodes (R_f), i.e. $T_2 = f(R_f)$ was used for R_f values estimation developed for sedimentary hydrophilic rocks with inter-granular porosity under fully water-saturated conditions. The results are:

- The T_2 spectra of the Berea samples and cuttings (size 3.35 – 6.35 mm) are equivalent in all T_2 values. The maximal value of filtration radius for this rock is $R_f \approx 20$ μm. The pore volume with pores $R_f \geq 5$ μm ($T_2 > \sim 80$ ms) is equivalent $\sim 65\%$ (see Figure 2.)
- The T_2 spectra of the Berea samples and the smaller cuttings (size 1.0-3.35) are different. The value of pores with filtration radii

$R_f \geq \sim 20$ μm ($T_2 > \sim 230$ ms) is less in this rock. The pore volume with pores $R_f \leq 1$ μm ($T_2 < \sim 25$ ms) is significantly higher.

- The T_2 spectra of the FCR sample (Fish Creek Outcrop) and cuttings with sizes 1.0 – 3.35 mm and 3.35 – 6.35 mm are equivalent in all T_2 values. According to relations $T_2 = f(R_f)$ the maximal value of filtration radius is $R_f \approx 20$ μm. The pore volume with pores $R_f \geq 5$ μm ($T_2 > \sim 80$ ms) is equivalent $\sim 35\%$ (compare Table 2).
- The experiments demonstrate that NMR can be used to estimate porous media parameters.
- For sedimentary rocks with inter-granular porosity the minimum cutting size for NMR characterization is dependent on porous media structure.
- The results agree with SEM/BSE image analysis techniques. They demonstrate that more NMR information of the petrophysical parameters can be obtained for cuttings larger >3 mm.

VERIFICATION OF POROSITY AND PERMEABILITY ESTIMATION OF DRILL CUTTINGS

In order to ensure the reliability of the measurements, we confirmed the porosity and permeability estimates with independent measurements where possible and by comparison with their core equivalent.

Prior work on porosity determination

The feasibility of using NMR to determine porosity on cuttings larger than 3 mm was shown by Akselrod et al. (1990), and Tulbovich (1979, 1990). The results came from hundreds of samples (carbonates and clastics @ $S_w = 100\%$) and had a relative error of 10%. The porosity variation was 1.4% - 27.6%. The NMR porosity values were compared to Archimedes porosities.

A similar study showed (Akselrod et al., 1990, Tulbovich, 1979, 1990):

- Cutting porosity estimates on clastics (range 4% - 23.7%) can have a mean square error of ±1.7%.
- The porosity estimates of carbonates were systematically understated by 2.2% compared

to direct method (Archimedes) on core plugs from the same intervals. The investigated rocks represent mixed (primary + secondary) and inter-granular (primary) porosities.

Our review showed:

- Inter-granular porosity in fully water saturated clastics can be estimated by NMR for cuttings ≥ 3 mm with sufficient accuracy for real-time well site solutions of wide range of problems.
- The information of carbonate cuttings depends on vug size and any other secondary porosity influence factors.
- The use of smaller than 3 mm cuttings needs further investigation.

NMR porosity estimation for pay zones must consider multi-saturation conditions (oil and water). NMR logging shows that porosity estimates are acceptable for most cases (Coates at al., 1999). However, the NMR porosity determined from non-water-wet (hydrophobic) porous media is systematically understated with respect to real porosity. Thus, NMR porosity estimates of cuttings can only be used when the measurements are not affected by anomalous formation fluids and wettability conditions.

Experimental considerations for porosity determination

The experiments on artificial rocks were carried out with different saturations.

The artificial rocks were created from mixture of different sands and clays under control of their composition. Their NMR properties were measured under the following saturations:

- Fully water saturated media ($S_w = 100\%$);
- Light oil saturated porous media at different S_{wirr} ($S = S_{wirr-i} + S_{oil-L}$);
- Heavy oil saturated at different S_{wirr} ($S = S_{wirr-i} + S_{oil-H}$).

The results are used for comprehension of the conditions for NMR application where *unbiased,* error free estimates can be recovered indicating the fluids properties. The studied conditions are an extreme because the samples represent reservoirs with very high porosity

(~40%) and wider range of S_{wirr} conditions than in real porous hydrocarbon bearing reservoirs.

The artificial samples were studied under the following conditions:
- Water saturation under vacuum (S_w=1) + NMR measurements;
- Irreducible water saturation (S_{wirr}) was simulated in capillary pressure chamber under 80 psi differential pressure + NMR measurements;
- 25 samples/models @ S_{wirr} were saturated by oil (S=$S_{wirr+oil}$) with viscosity μ=27.9 cPs+ NMR measurements;
- 23 samples @ S_{wirr} were saturated with oil (S=$S_{wirr+oil}$) with a viscosity μ=8.4 cPs +NMR measurements.

The water (W_{water}) and oil (W_{oil}) content was verified by repeated sample weighting. The oil and water densities were measured as well. The control measurements were used for porosity verification (hydrogen content – V_H) where V_H = POROSITY*V_s under S_w=100% and $S_{wirr+oil}$. Vs is sample volume. These results are obtained when the whole NMR signal is measured. V_H and W_{water} are equivalent to volume moisture (ω) in rocks under S_w=S_{wirr} conditions. The NMR data from the artificial samples yield V_H estimates in the typical parameter range for sediments (porosity ~2% to ~40%). Volumes of samples are 10 cm³. Figure 3 shows the results.

Data from the literature (Kenyon, 1992; Vinegar, 1995; Coates et al., 1999) demonstrate that V_H (or porosity) of fully saturated (water/oil, μ~30cPz) core samples can be estimated with accuracy ~± 1.5% . Two factors influence the NMR porosity determination:
- appropriate fluid volume in cuttings with optimum particle size;
- Errors in bulk sample volume.

The results of the artificial samples are:
- NMR can determine inter-granular porosity in ≥2 mm with acceptable accuracy (0.5%-1.3% @ absolute porosity 15%-20%)
- NMR method yields porosity of fully water or oil saturated (viscosity μ≤30 cPs) cuttings.

- Sample quantity (volume), cuttings size, (particles' less than 2mm) and errors in volume determination are factors that can negatively influence porosity values.

Permeability determination of drill cuttings
Two tasks must be solved to substantiate permeability estimates from cuttings:
- Determine minimum cuttings size.
- Determine of NMR parameter relationships (T_2 and amplitude A_t) recovered for different saturation and permeability.

The core samples and cuttings used are not sufficient to address above issues. In addition, different interpretation models (Free Fluid Model and T_2 mean model, Coates, et al., 1999) must be included. These data were obtained from consolidated and un-consolidated porous media.

Experiment considerations for permeability determination
We determined minimal cutting size for PERM estimates for a minimum error in permeability estimates (PERM=f(A_t,FFI,BVI)), where FFI-free fluid index, BVI-bound water). We did not include unfavorable measurement conditions (non-water wet, viscous oil in pore space, etc.)
The Free Fluid Model (FF) is based on relationship between porosity and S_{wirr} data. The input data for FF model investigation (simulation and direct PERM determination on core samples (**K***)) are in Table 3.
The porosities for simulation of PERM data on cuttings were identical to the porosities from respective cores. This approach does not include geometrical volume (V_g) errors. The total amplitudes of NMR signal from plugs and cuttings were comparable.
The error in V_g can be caused by:
- Non-proper sample preparation technique;
- Non-optimized V_g measurement procedure;
- Insufficient sample's volume;
- Non-appropriate V_g measurement device.

The interpretation model for NMR PERM estimates is called MR-ML™ model:

$$PERM= f(\emptyset_{eff}, PSD, GSA),$$

Where the effective porosity is Øeff, PSD-pore size distribution, GSA- results of grain size analysis. The model is for permeability determination of the samples in six clusters.

The classification of the clastics (six clusters) can be found in Khanin (1976). The solutions for MR-ML™ model was found as

$$LgPERM=a* \emptyset_{eff} + b.$$

The coefficients a, b were found for each cluster. Principals/criteria for $\emptyset_{eff}$ determinations were developed using a generalized NMR parameters (T_2 spectra) for each cluster. The NMR data for the core samples (172) were measured under different saturation conditions.

The model includes as empirical parameters:

- Minimum (M_{effmin}) and maximum (M_{effmax}) effective porosity for filtrating pores with $R_f \geq 5$ µм and $R_f \geq 2$ µм, respectively.
- Lithology of studied/measured rock sample.

The INPUT information for model usage is: A-NMR spectra (T_2 vs. A_t) and B-visual lithology estimation/description (examples: (a) coarse grained sandstone, (b) fine grained siltstone, etc.). The MR-ML^{TM} model is independent on saturation conditions (conventional oils with viscosity up to 20 cps.or brine) and covered most of the clusters representing clastic rocks. The MR-ML™ model is simplified model for automated implementation.

Respective PERM estimates are in Table 4 for the MR-ML™ model. The studied samples included fine-grained and medium-grained sandstones that can be appropriately used for physical simulation of the porous media topology and saturation conditions described (represented) by developed model.

The agreement between the absolute permeability and the central value of minimum and maximum MR-ML™ perm in table 3 and 4 shows that NMR can be used for PERM estimates for cuttings as small as 1 mm.

Summarizing the results:

- NMR PERM estimates for cuttings are comparable estimates from cores. Even for

the 1-3 mm Berea sandstone cuttings the agreement in PERM is good.

- For clastics cuttings size larger 1 mm is acceptable for PERM estimates with NMR.
- The studies with respect to cutting size and different grain size must be continued. Additional experiments must include coarse-grained and medium-grained sandstones with high permeability (**≥100** mD). In most cases (from NMR data), the samples represent rocks with $R_f > 10$ µм and $R_{mf} > 20$ µм.
- The minimal size requirements are stricter for porous media structure than for permeability simulation. Thus, the T_2 spectra compatibility for cuttings and samples (under $S_w=100\%$) is an additional requirement to substantiate that PERM estimates can be obtained with NMR.

MODEL VERIFICATION FOR PERMEA-BILITY DETERMINATION

To derive permeability for clastics a correlation between T_1 and T_2 values for water saturated rocks and known pore size distribution (PSD) is required. Respective laboratory studies are published by Lukianov (1989), Akselrod et al. (1990), Tulbovich (1990) and others. The two most common models for permeability estimation are (Coates et al., 1999):

- Model M1: Mean T_2 Model:

$$PERM=aT_{2gm}{}^2POR^4$$

- Model M2: Free Fluid Model.

$$PERM = [(\frac{POR}{c})^2 (\frac{FFI}{BVI})]^2$$

Model M1 adopts information from T_2 (T_1) spectra and respective pore size distribution (PSD). The M1 model works well in zones containing only water a rock with water wet pore wall. When oils or oil filtrates are present, the mean T_2 is overestimated and T_2 and permeability estimates are erroneous. The results of M1 are affected by wettability conditions, unknown oil distribution in porous media, oil properties etc. In un-flushed gas zones, mean T_2 values are too low

relative to the flushed gas zone, and permeability is consequently underestimated because hydrocarbon effects on T_{2gm} are not correctable. The M1 model fails for hydrocarbon-bearing formations.

M*odel M2* is based on relationships of PERM with porosity and S_{wirr}. It includes $T_{2cutoff}$ for S_{wirr} estimates taking into account the properties of studied deposits and saturating fluids. It includes dependency on the sedimentation process lithology. The M2 model is more flexible than the M1 model. The M2 model can be customized for different formations and oil reservoirs based on core calibration. "As long as BVI does not include any hydrocarbon contribution, BVI is not affected by an additional liquid phase such as oil or oil filtrates, which is very important when analyzing hydrocarbon-bearing formations" (Coates et al., 1999). This model is widely used for NMR logging data interpretation. Heavier oils, which normally have very short T_2 values, may be counted as BVI*, thus causing permeability to be underestimated.

The M2 model has the following advantages over the M1 model:

- It is more applicable for reservoirs with different saturation conditions. The FFI data have to be normalized according to difference in water and oil's hydrogen indexes.
- It can be applied for NMR data processing for estimation of the total amplitude of NMR signal. The signal is proportional to porosities in water- and oil-bearing deposits. As first approximation, short T_2 values are related to signal from bound water –BVI, but long T_2 terms are related to content of free fluid –FFI.

Comparing direct PERM measurements on core samples PERM estimates from NMR logging (PERM$_{NMRlogging}$) indicates:

- Using M1 and M2 models without the learning process from core samples can yield systematic errors in the PERM$_{NMRlogging}$ data (Mirotchnik, et al., 1998). This can be important for decision-making.

Errors in PERM$_{NMRlogging}$ are limited by:

- M1 and M2 models are developed for fully water saturated rocks with water-wet (hydrophilic) pore surface (S_w=100%). In reality, these models are applied for PERM$_{NMRlogging}$ estimates with multi-saturations with non-water wet pore surface.
- M1 and M2 models are not universal for realistic structure variations, textures and mineral composition.

Tables 5 and 6 show the results of PERM estimates from unconsolidated models (within the framework of M1 and M2 models).

These data clearly illustrate the shortcomings of M1 and M2 models related to NMR PERM determination. Similar estimates will be done on cores under $S=S_{wirr}+S_{or}+S_{w\_movable}$ saturation conditions. This type of saturation is typical for drill cuttings collected from wells drilled with water based mud.

The MR-ML™ model for PERM estimates is not influenced by saturation conditions.

The results of permeability determination on artificially made cuttings with application of MR-ML™ technology in comparison with direct permeability determination on the same plugs (111 samples) are presented in Figure 4.

Porosity and permeability results from ML - ML™ technology are shown in Figures 5 and 6. Cuttings were from Jurassic clastics (Western Siberia).

CONCLUSIONS

- The values of PERM$_{NMR}$ obtained by applying correct models using PERM$_{\_direct}$ demonstrate that PERM$_{NMR}$ is ***sufficient*** for on-line PERM estimates on cuttings (clastics).
- The PERM$_{NMR}$ yields estimates of absolute permeability and is sufficient for definition of productive intervals in wells.
- NMR measurements performed at ambient (standard) conditions on cuttings saturated by light oils (<20 cPs) must be performed on cuttings samples saturated by viscous oils (>20 cPs) at elevated temperature or use S_{oil} that has been previously determined by NMR on investigated samples.
- NMR data lends itself to grouping of sediments (including productive deposits) into clusters with different permeability and

effective porosity. Testing of the MR-ML™ model for these purposes on cuttings, cores and ground samples under appropriate conditions for model usage will be carried in the future.

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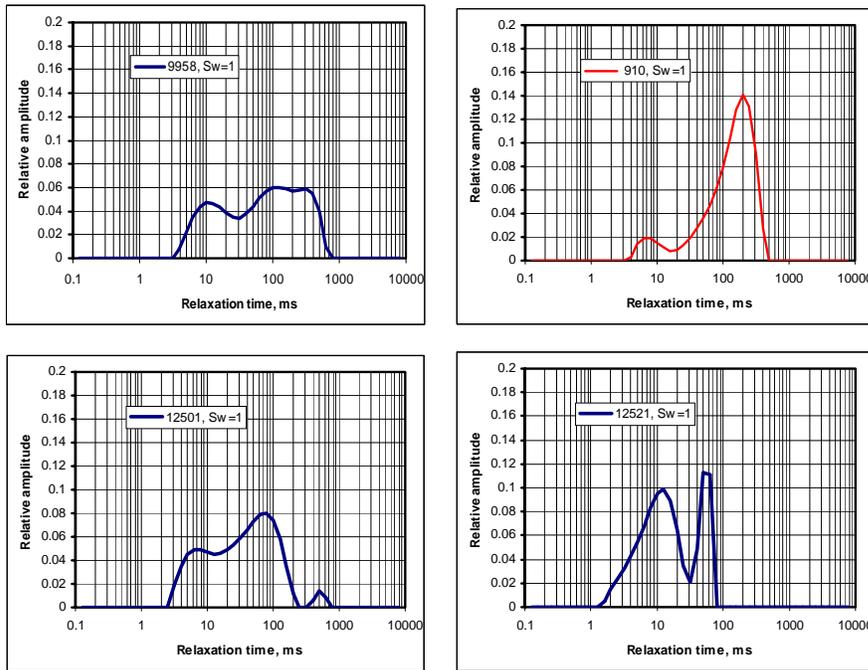
Figure 1: NMR differential spectra for four samples with 100% brine saturation conditions (2% NaCl).
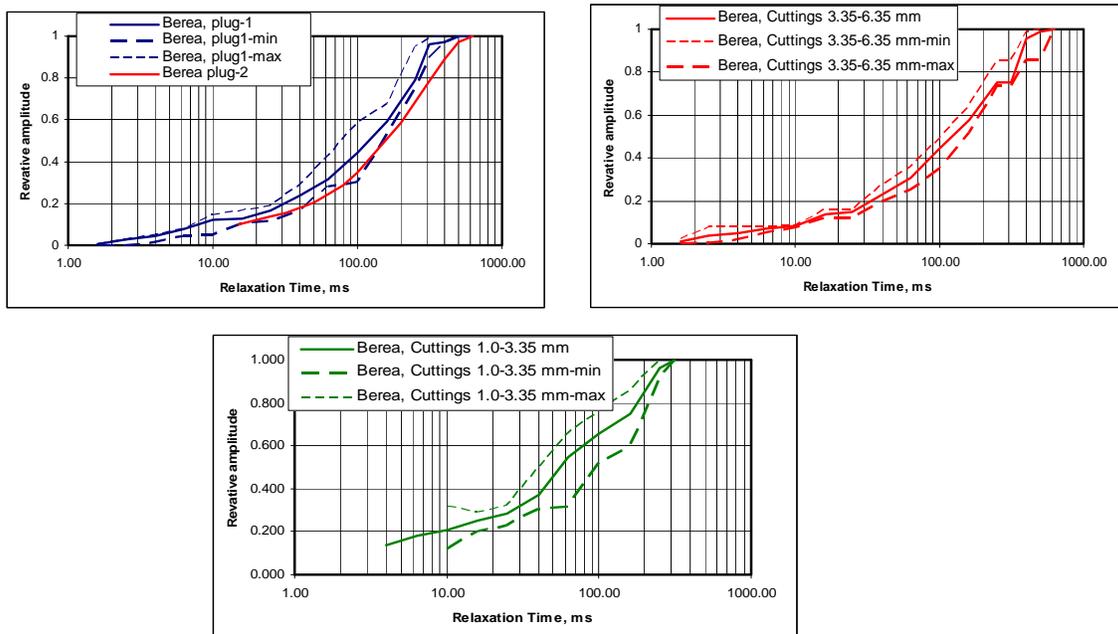

Figure 2: Example of the cumulative curves (T$_2$ spectra) delivered from Berea Plug 1 (core samples and cuttings).
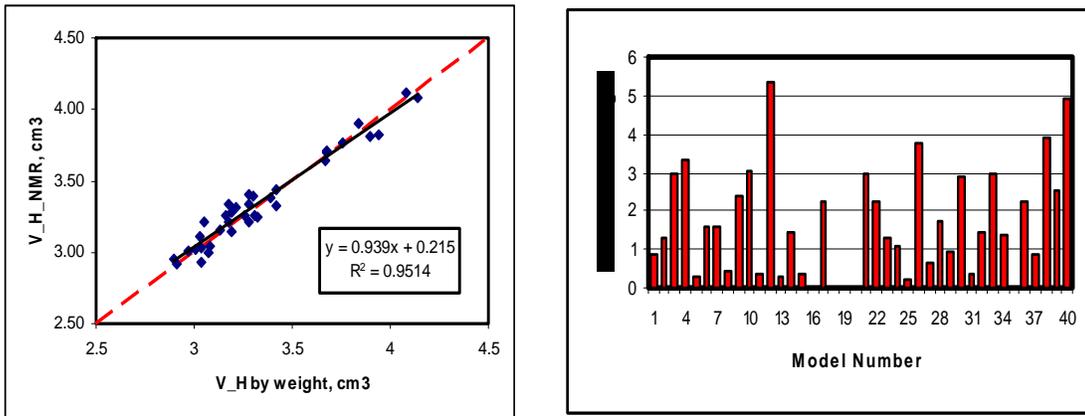
Figure 3:   a) Comparison V_{H_weight} vs. V_{H_NMR} b) The relative errors in V_H determination.
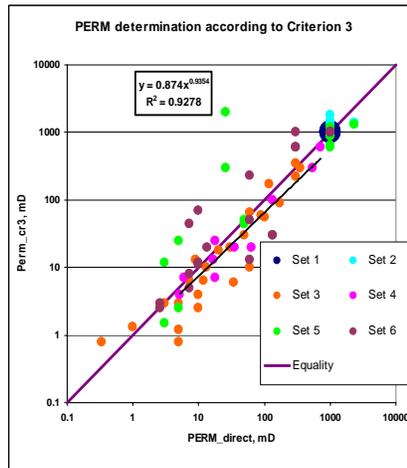

Figure 4.   Comparison of PERM estimates according to criteria 2 and 3 with PERM values determined directly.
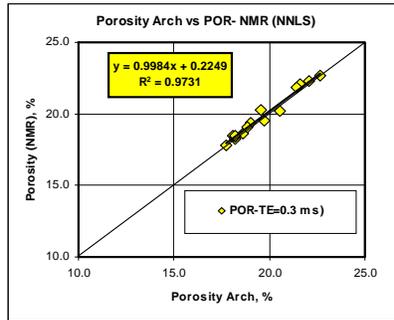
Figure 5. Porosity by Archimedes vs. NMR Porosity

| A | B |
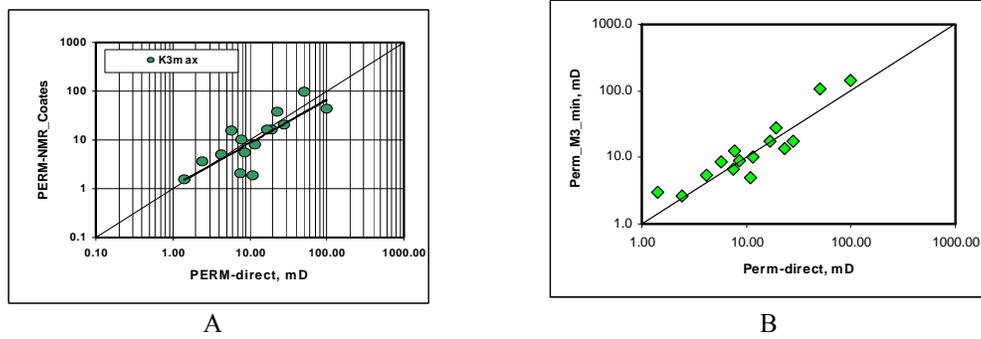
Figure 6. PERM$_i$_MR-ML vs. PERM$_i$_direct for Sw=100% (A) and S=S$_{wirr}$+S$_{oil}$ (B) conditions.

Table 1a: Petrophysical parameters of samples (outcrops).

Sample ID	ø,%	PERM,mD	Swirr @ P$_c$=DPpsi,%	T$_{2mf}$*, ms	R $_{mf}$, μm	Lithology
Berea-1	30	15.7	16.7	200	~18	sandstone
Berea-2	16.9	70.5	15.5	230	~20	sandstone
FCR	20.6	12.7	46	100	~7.5	sandstone

*/ **T$_{2mf}$**– modal T$_2$ values for main group of pores influenced on fluids dynamics
in porous media (R$_f$≥5μм) @ **S$_w$=100%**.

Table 1b.   Petrophysical parameters of investigated set samples

Sample ID	ø ,%	Perm,mD	S_{wirr},%	Grain Size
9958-01	18	23	42.9	medium/fine
9921-01	17.1	11.6	45.1	medium/fine
9945-01	18.8	99	33.3	medium/fine
910-01	20.7	50.8	25.4	medium/fine
3322-90	22.3	7.6	48.5	Fine
3341-90	21.6	11	45.5	Fine
12501-01	22.8	19	41.7	medium/fine
12521-01	18.5	1.42	65.1	Fine
12505-01	21.43	4.2	53.64	medium/fine
8589-00	18	2.4	53.3	medium/fine
8531-00	18.1	5.68	47	medium/fine
8582-00	18.8	7.8	45.3	medium/fine
8575-00	18.8	8.7	48.8	medium/fine
8504-00	19.7	16.7	42.6	medium/fine
8502-00	20.4	28	38.8	medium/fine

Table 2:   Results of FCP determination on investigated set of outcrop samples

Pore Radius	Berea			FCR		
R_f,	plugs	cutting>3.3mm	Cutting 1-3mm	plug	cutting>3.3mm	Cutting 1-3mm
microns	a, %	a, %	a, %	a, %	a, %	a, %
>30	4 - 21.5	~15	0	0	~1	0
~30	10-14.3	~10	~4	~4	~1	0
~23	17.7-1.8	~18	~21	~9	~5	~3.5
~13	15.8-2.9	~13	~9.5	~7	~6	~9.5
~7	2.30-10	~13.5	~11	~17	~20.5	~19.5
~4	6.7-11.4	~7.5	~17	~10	~12	~14.5
~2	7.4-14.6	~8	~9	~9	~7	~10
~1	~3.5	~1	~3.5	~6	~11	~2.5
<1	~10-11	~14	~25	~36	~37	~36.5

Where a,% - percentage from pore volume presented by pores with R_{f_j}.

Table 3: PERM estimates FF (Free Fluid) model from core and cutting samples.

Sample	K*, mD	NMRPOR, %	Swirr,%	K, mD, by Free Fluid model	Cuttings size
Berea-1	38	15.3	16.7	136.3	
Berea-2	70.5	16.9	15.5	242.4	
Cutting Berea	38-70.5	16.1	15.9	188	3.3 - 6.3 mm
Cutting Berea	38-70.5	16.1	33	27.7	1 - < 3.3 mm
Sample FCR	12.7	20.6	46	24.8	
Cutting FCR	12.7	20.6	50	18	3.3 - 6.3 mm
Cutting FCR	12.7	20.6	44.4	28.2	1 - <3.3 mm

Where **K*** - absolute permeability (gas) determined by standard method (steady state).

Table 4: PERM estimation by PERM=f(POR$_{eff,}$ LIT) – MR-ML model

Sample/cutting	K*, mD	Meff_min, %	Meff_max, %	Kmin, mD	Kmax, mD	Cuttings size, mm
Sample Berea-1	38	9.6	13.1	18	70	
Sample Berea-2	70.5	12	14	45	100	
Cutting Berea	38-70.5	9.2	13.5	15	80	3.3 – 6.3
Cutting Berea	38-70.5	7.3	10.8	7.5	30	1.0 – 3.3
Sample FCR	12.7	8.3	11.1	10	32	
Cutting FCR	12.7	6.8	10.2	6	22	3.3 – 6.3
Cutting FCR	12.7	7.5	11.4	8	35	1.0 – 3.3

Table 5: Comparison of PERM-NMR (M1) with PERM-direct @ Sw=1, S=Swirr+ Slight oil & S=Swirr+Sheavy oil BVI as apportion of pore volume PERM_NMRj as portions of PERM @Sw=1

Set-ID	Swirr, %	Sw=1	Swirr+LO	Swirr+HO	Sw=1	Swirr+LO	Swirr+HO
1 (1-10)	5.5	0.05	0.1	0.29	1	0.47	0.13
2(21-30)	8	0.07	0.1	0.27	1	0.68	0.20
3(11-20)	18	0.12	0.19	0.33	1	0.58	0.28
4(41-50)	37	0.5	0.39	0.59	1	1.56	0.69

Notes: LO -light oil
              HO -heavy oil

Table 6: Comparison of PERM-NMR with PERM-direct @ Sw=1, S=Swirr+ Slight oil & S=Swirr+Sheavy oil Geometric T_2 values PERM_NMRj as portions of P
ERM @Sw=1

Set-ID	Swirr, %	Sw=1	Swirr+LO	Swirr+HO	Sw=1	Swirr+LO	Swirr+HO
1 (1-10)	5.5	480	155	40	1.00	0.32	0.08
2(21-30)	8	150	120	30	1.00	0.80	0.20
3(11-20)	18	190	135	35	1.00	0.71	0.18
4(41-50)	37	100	100	33	1.00	1.00	0.33

Notes: **LO-light oil**
              HO-heavy oil