MRS2015 / 6th International Workshop on Magnetic Resonance

Localizations and fluid characterization of a thin oil layer using a slim NMR borehole tool

Raphael Dlugosch
Leibniz Institute for Applied Geophysics
Stilleweg 2, 30655 Hannover, Germany
Raphael.Dlugosch@LIAG-Hannover.de

Thomas Günther
Leibniz Institute for Applied Geophysics
Stilleweg 2, 30655 Hannover, Germany
Thomas.Guenther@LIAG-Hannover.de

Tamàs Lukàcs
Eötvös Loránd University
Egyetem tér 1-3, 1053 Budapest, Hungarian
lukacs.tom@gmail.com

Mike Müller-Petke
Leibniz Institute for Applied Geophysics
Stilleweg 2, 30655 Hannover, Germany
Mike.Mueller-Petke@LIAG-Hannover.de

SUMMARY

Since a few years a slim borehole tool, designed for shallow hydrogeological applications, is commercially available. We evaluate and improve its performance to detect and characterize hydrocarbon contaminations. The objectives of this work are (i) to increase the natural spatial resolution of the achieved NMR logs of 0.5 m to be able to detect thin layers, (ii) to study the performance of the probe to characterize fluids using NMR diffusion measurements.
To increase the spatial resolution of the obtained NMR logs we jointly invert several measurements conducted with overlapping sensitive volumes. This leads to a significantly increased spatial resolution of the NMR relaxation time logs. To clearly distinguish and quantify water and oil phases due to their contrast in the diffusion coefficient we utilize CPMG pulse sequences with different echo spacings. Finally, we combine both approaches which enables NMR relaxation time logging and fluid typing with an increased spatial resolution.

Key words: borehole NMR, diffusion measurements, fluid typing, spatial resolution, hydrocarbon.

INTRODUCTION

The method of nuclear magnetic resonance (NMR) has been developed in the 1940s by Bloch *et al.* (1940) and Purcell *et al.* (1946). The method proofed to be a useful tool in geosciences especially since the introduction of the first borehole application in the 1960s (Brown and Gamson, 1960). It started with measuring the free-induction decay which enables concluding about porosity and pore size. Since then the application of borehole NMR has developed. The measurements were improved using a Carr-Purcell-Meiboom-Gill (CPMG) experiment to estimate the transversal NMR relaxation time (T_2) which provides a more reliable measure for the pores size. One of the latest developments in NMR pulse sequences enables estimating the diffusion coefficient (D) of a fluid by varying the echo spacing (TE) of the CPMG sequence conducted in the artificial magnetic gradient field of the probe (Paltiel, 1992; Hürlimann and Venkataramanan, 2002). In contrast to T_2, which comprises pore size and fluid information, D enables a less ambiguous fluid typing, e.g. to distinguish the water, hydrocarbon and gas phases.

There are different processing schemes available to separate the NMR signal originating from fluid phases with different D. The early approaches subtract time domain signals or T_2 distributions of experiments conducted using different TE times (Prammer *et al.*, 1995; Akkurt *et al.*, 1996, 1999). More advanced approaches explain the measured NMR data using an inversion based on a multi-phase model, e.g. consisting of T_2, the longitudinal NMR relaxation time and D (Freedman *et al.*, 2000).

Since a few years a slim borehole tool (Javelin, Vista Clara Inc.), designed for shallow (<220 m) hydrogeological applications, is commercially available. In this work we use the JP350 probe which has a diameter of 8.9 cm (3.5''). The sensitive volume of the probe has the shape of a vertically orientated thin cylinder shell with a radius of approx. 19 cm and a height of approx. 0.5 m (Figure 1). To obtain an acceptable signal to noise ratio, a sequential measuring scheme is suggested by the manufacturer where the probe is kept fixed at one depth and the signal is stacked over several NMR excitations until an acceptable signal quality is reached. Subsequently, the probe is lowered or raised by at least the height of the sensitive volume (0.5 m) for the next measurement. This leads to a natural spatial resolution of the achieved logging of >0.5 m.

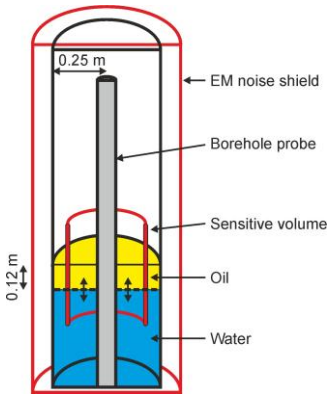

Figure 1. Laboratory setup of the borehole NMR probe JP350 placed in a water tank including a 12 cm thick rapeseed oil layer at variable depth. EM shielding is achieved using 2 mm thick aluminium plates.

The two objectives of this work are (i) to increase the spatial resolution of the achieved NMR logs and (ii) to conduct NMR diffusion measurements leading to an improved fluid typing. To increase the spatial resolution of the obtained NMR logs we jointly invert several NMR measurements conducted with overlapping sensitive volumes. We show the successful application in a water tank using a rapeseed oil layer which shows a significant contrast in T_2 (Figure 1). To clearly distinguish and quantify the water and oil phase due to their contrast in D we use CPMG pulse sequences with different TE. Finally, we combine both approaches. Several NMR measurements with overlapping sensitive volumes were conducted with a subsequent variation of TE with depth. The obtained data are jointly inverted using a T_2-D-depth model. This enables estimating T_2 and D with an increased spatial resolution.

METHOD AND RESULTS

Estimation of probe sensitivity

To estimate the sensitivity of the NMR probe a high resolution logging with a step size of 3 cm was conducted crossing a water table (Figure 2). The measured cumulative water content can be explained by a trapezoid sensitivity function with a height of 36 to 72 cm centered 0.935 m below the cable head of the probe.

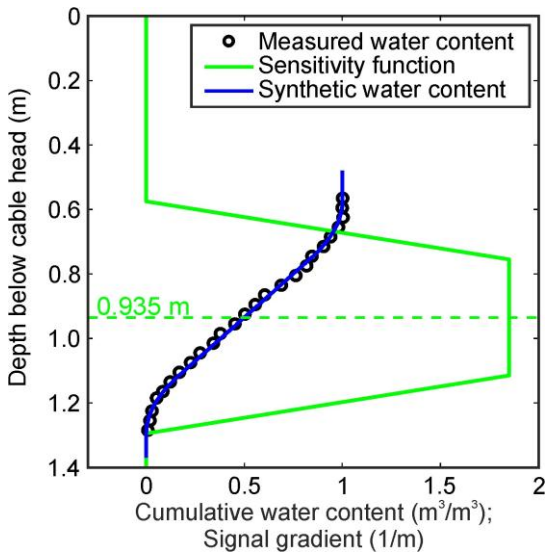

Figure 2. Sensitivity of the JP350 probe. Measured cumulative water content (black circles) obtained from a high resolution logging crossing a water table. Estimated sensitivity function (green) and resulting synthetic cumulative water content (blue).

High spatial resolution T_2 logging (HRT)

To increase the spatial resolution of the T_2 logging below the height of the sensitive volume (0.5 m) of the probe, several NMR measurements with overlapping sensitive volumes were conducted (Figure 3 a) and jointly inverted. We use an iterative inversion approach based on a Gauss-Newton Algorithm as described by Mueller-Petke and Yaramanci (2010). The objective function to be minimized consists of a term for the data misfit weighted by the data error and a term including the first-order flatness matrix which ensures a smoothness-constrained solution.

We show the capability of this approach using an experimental setup consisting of a 12 cm thick oil layer on top of a bulk water layer presented in Figure 1. Both bulk fluid layers show a significant difference in the estimated T_2 times (rapeseed oil: 0.1 s and water: 1s) measured including the diffusion effect in the magnetic gradient field of the probe.

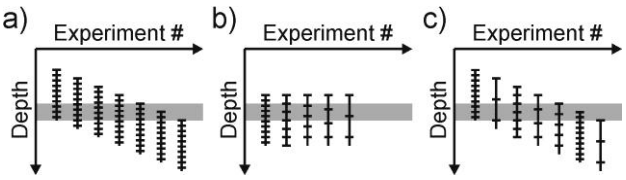

Figure 3. Sketch of the NMR experiments used to resolve an oil layer (gray). High spatial T_2 logging (a), D measurements (b) and high vertical resolution T_2-D logging (c). Depth distribution of the sensitive volume (height of vector) and TE (tick spacing).

A comparison of a low resolution logging (sampling rate: 0.5 m) and a high resolution logging (sampling rate: 0.06 m) is presented in Figure 4. The different T_2 times of both layers can be clearly distinguished by both loggings. The NMR experiment of the low resolution logging conducted at around 1.68 m summarizes over three layers, air, oil and water. Without further knowledge, this part of the low resolution logging might be misinterpreted as a low porosity layer with a

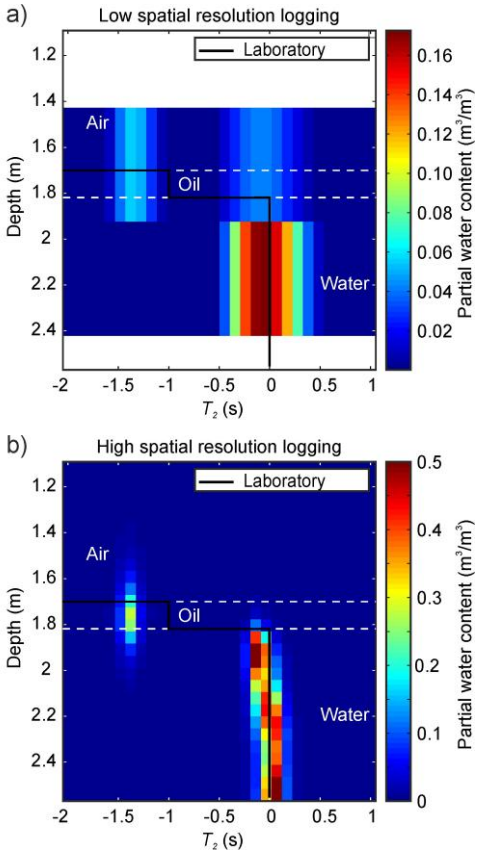

Figure 4. Comparison of low (a) and high (b) spatial resolution logging conducted on a three layer setup (air, oil, and water). Layer boundaries (white dashed lines) and T_2 of rapeseed oil and bulk water (black line) from laboratory NMR measurements for reference.

multiexponential NMR signal. The high resolution logging resolves the experimental setup with increased spatial resolution. Because of the applied smoothness constraints, the sharp boundaries of the layers appear blurred. Additionally to the increased spatial resolution, the T_2 time of the bulk water is better resolved due to the increased number of NMR measurements.

Diffusion measurement

The diffusion coefficient of a fluid affects T_2 measured in a magnetic gradient field (ΔB_0) using a CPMG sequence dependent on *TE*. The impact on T_2 can be described by:

$$\frac{1}{T_2} \approx \frac{D(\gamma \Delta B_0 TE)^2}{12} \quad , \tag{1}$$

where γ is the gyromagnetic ratio of protons (Kleinberg. and Horsfield, 1990).

To estimate *D* and T_2 of the experimental setup presented in Figure 1, the NMR probe was placed in the transition region of air, oil and water (fractions: 0.2/0.2/0.6). Five NMR experiments with logarithmically equidistant spaced *TE* values ranging from 2.5 to 21 ms (Figure 3 b) were conducted to identify and quantify the oil and water phase.

We use the inversion approach described for the HRT logging to find a smooth T_2-*D* model, which explains the measured data within the noise level. The obtained result is presented in Figure 5 as a T_2-*D* map and resulting T_2 and *D* spectrum. Both fluids show a significant contrast in T_2, which is well resolved and allows distinguishing both fluids using a cut-off time of 0.4 s. In contrast to the results presented in Figure 4, the estimated T_2 times are no longer affected by diffusion in magnetic gradient field. While *D* of water can be well estimated, the very low *D* value of the rapeseed oil is not well resolved. Because of the comparably low magnetic gradient field of the JP350 probe, long *TE* times are required to achieve detectable T_2 variation (Equation 1). This leads to a low signal to noise ratio of the recorded fast relaxing oil signals. Although only an upper limit of *D* can be estimated for the rapeseed oil, a cut-off *D* of 4e-10 m^2/s allows quantifying both fluids. This might be less an issue for hydrocarbons, which generally show higher *D* values.

Because the sampled volume contains only two bulk fluid phases, a simple two-phase model with a single respective T_2 and *D* value was used to explain the measured data within the noise level. The hence estimated T_2 and *D* values as well as the quantities of oil and water (Figure 5) agree well with the expectations.

High spatial resolution T_2-*D* logging (HRTD)

Both approaches, the high spatial resolution logging and the diffusion measurement, can be combined to a T_2-*D* logging with an increased spatial resolution. We apply this approach on the experimental setup presented in Figure 1. Each of the 14 NMR measurements was conducted with a single, constant *TE* time. After each measurement the depth of the tool was changed by 6 cm (Figure 3 c) and a new *TE* was selected. The five *TE* values were cycled to ensure a complete coverage of the logged volume by CPMG experiments with all *TE* times.

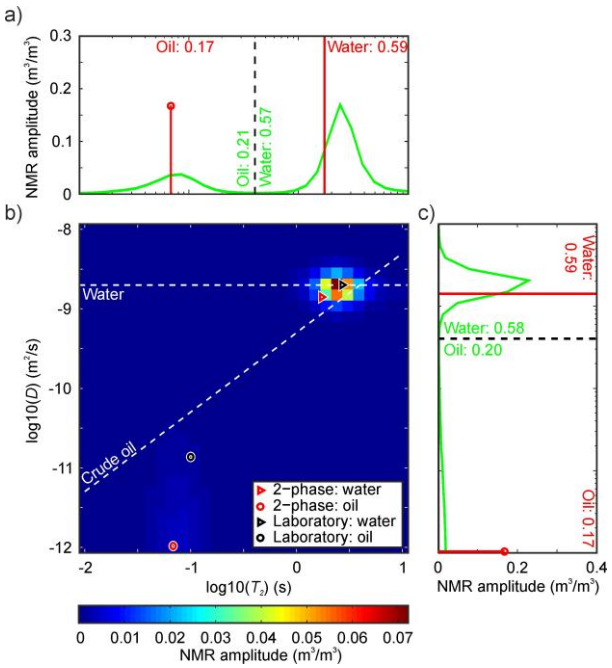

Figure 5. Diffusion measurement conducted on a three layer case consisting of air, rapeseed oil and water. Estimated T_2-*D* map (b) with respective T_2 (a) and *D* spectrum (c) (green line). Cut-off values for T_2 and *D* (black dashed line) to estimate the respective quantities of oil and water. Result of the two-phase model (red markers and values). Contour lines (b) for water and crude oil after Hürlimann et al. (2002) (white dashed line) and laboratory measurements (black marks) for reference.

The smooth inversion approach presented for the HRT logging has been advanced to the 3D model space (T_2-*D*-depth). The obtained model cube explains the data within the noise level and is a presented in Figure 6 as sum maps of each dimension. They enable identifying and locating both fluid phases based on their respective *D* and T_2 values. The model resolution is lower compared to the HRT logging because of the increased number of NMR experiments with long *TE* times leading to an overall lower signal to noise ratio of the data set.

Because of the blocky characteristic of the experimental setup a block inversion was conducted on the measured data set. The result presented in Figure 6 explains the data equally well within the noise level but leads to better estimation of the model parameter.

CONCLUSIONS

The results presented in this work shows that the natural spatial resolution of the NMR logging of 0.5 m when utilizing the slim NMR probe JP350 can be increased by conducting multiple NMR measurements with overlapping sensitive volumes and a subsequent inversion. This enables resolving a layer with a thickness of 12 cm. A variation of the CPMG echo spacing enables a fluid typing based on the diffusion coefficient. Combing both approaches leads to a logging of the NMR parameters relaxation time and diffusion coefficient with an increased spatial resolution.

Because of safety reasons, the presented experiments were conducted using rapeseed oil. All results should be transferable to hydrocarbons which generally show higher diffusion coefficients. Therefore, the comparable low magnetic gradient, which significantly limits the potential of the JP350 probe to resolve very low diffusion coefficients, are less an issue. On the other hand, the smaller contrast in the diffusion coefficients of water and hydrocarbons offers a new challenge. The resolution of NMR parameters is generally limited by the quality of the recorded NMR signals. The signal quality of the presented data can be further improved by (i) shorter CPMG echo spacing, (ii) using a diffusion editing sequence which varies only the spacing of the first CPMG echo and samples the NMR signal using a high resolution CPMG (Hürlimann and Venkataramanan, 2002), (iii) using the additional information gained from NMR experiments conducted at multiple frequencies.

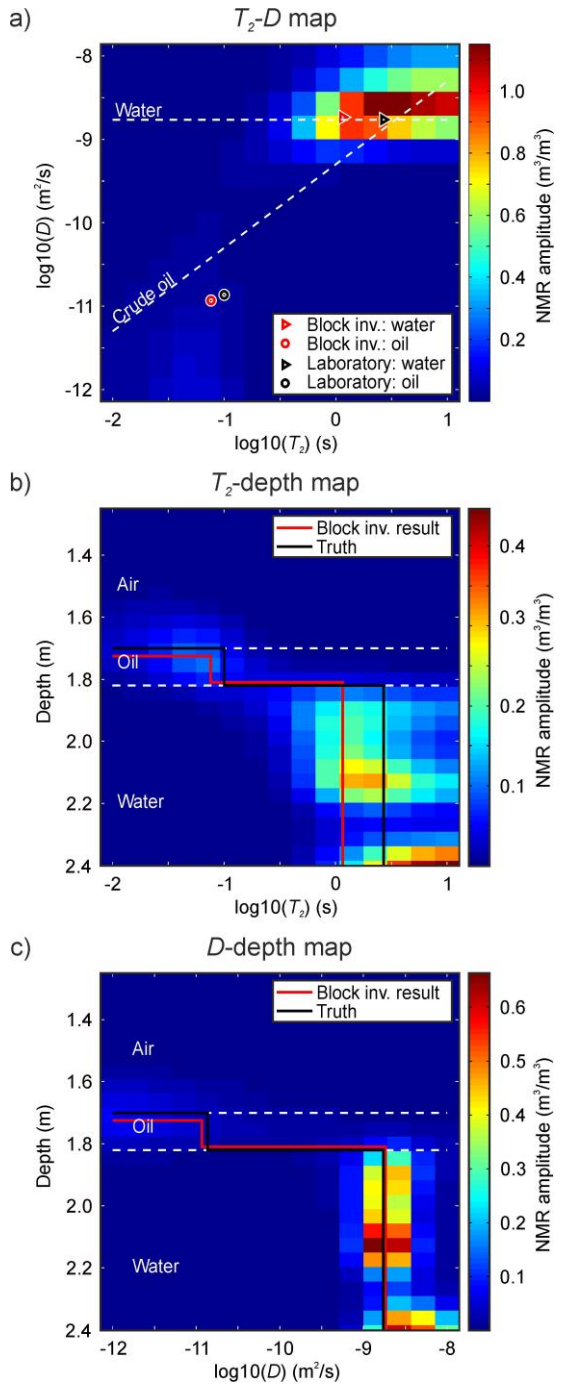

Figure 6: Diffusion logging with increased vertical resolution conducted on a 12 cm thick rapeseed oil layer on top of water. Estimated T_2-D (a), T_2-depth (b) and D-depth (c) maps. Contour lines (a) for water and crude oil after Hürlimann et al. (2002) (white dashed line). Expected layer interfaces (b and c) of the experimental setup (white dashed lines). Laboratory measurements (black marks and lines) for reference.

REFERENCES

Akkurt, R., Marschall, D., Eyvazzadeh, R.Y., Gardner, J.S., Mardon, D. and Dunn, K.J., 1999, Determination of Residual Oil Saturation by Use of Enhanced Diffusion: SPE Reservoir Evaluation & Engineering, 2 (3), 303–309.

Akkurt, R., Vinegar, H.J., Tutunjian, P.N. and Guillory, A.J., 1996, NMR Logging of Natural Gas Reservoirs: The Log Analyst, 37 (6), 33–42.

Bloch, F., Hansen, W.W. and Packard, M., 1946, The Nuclear Induction Experiment: Physical Review, 70(7–8), 474–485.

Brown, R.J.S. and Gamson, B.W., 1960, Nuclear magnetism logging: Journal of Petroleum Technology, 219, 199–201.

Freedman, R., Sezginer, A., Flaum, M., Matteson, A., Lo, S. and Hirasaki, G.J., 2000, A New NMR Method of Fluid characterization in Reservoir Rocks: Experimental Confirmation and Simulation Results: in SPE Annual Technical Conference and Exhibition, Dallas, Texas, p.15.

Hürlimann, M.D. and Venkataramanan, L., 2002, Quantitative Measurement of Two-Dimensional Distribution Functions of Diffusion and Relaxation in Grossly Inhomogeneous Fields: Journal of Magnetic Resonance, 157, 31–42.

Hürlimann, M.D., Venkataramanan, L. and Flaum, C., 2002, The diffusion-spin relaxation time distribution function as an experimental probe to characterize fluid mixtures in porous media: The Journal of Chemical Physics, 117 (22), 10223–10232.

Kleinberg, R.L. and Horsfield, M.A., 1990, Transverse relaxation processes in porous sedimentary rock: Journal of Magnetic Resonance (1969) 88(1), 9–19.

Mueller-Petke, M. and Yaramanci, U., 2010, QT inversion – Comprehensive use of the complete surface NMR data set: Geophysics, *SEG*, *75 (4)*, WA199–WA209.

Paltiel, Z, 1992, Apparatus and technique for NMR diffusion measurements: Patent App. PCT/US1991/009,045.

Prammer, M.G., Mardon, D., Coates, G.R. and Miller, M.N., 1995, Lithology-Independent Gas Detection by Gradient-NMR Logging: in SPE Annual Technical Conference and Exhibition, Dallas, Texas, 325–336.

Purcell, E.M., Torrey, H.C. and Pound, R.V., 1946, Resonance Absorption by Nuclear Magnetic Moments in a Solid: Physical Review, 69(1–2), 37–38.