diffusion-fundamentals.org
The Open-Access Journal for the Basic Principles of Diffusion Theory, Experiment and Application

Nuclear Magnetic Resonance Logging While Drilling (NMR-LWD): From an Experiment to a Day-to-Day Service for the Oil Industry

Martin Blanz, Thomas Kruspe, Holger Frank Thern, Gerhard Alfons Kurz

Baker Hughes Incorporated

Corresponding author: Martin Blanz, Baker Hughes, Celle Technology Center,
Baker-Hughes-Str. 1, 29221 Celle, Germany, E-Mail: Martin.Blanz@bakerhughes.com

(received 13 September 2010, accepted 19 November 2010)

Abstract

NMR T_2 distribution measurement is our chosen everyday method for NMR logging while drilling oil and gas wells. This method yields straightforward preparation and execution of the job as well as a normally easy interpretation of the measured data. For instance, gas and light oil discrimination against water is feasible by direct observation of the T_2 distribution. A condition for this measurement method is a NMR logging tool that hardly moves while drilling and in addition uses a small static magnetic field gradient and short inter-echo time *TE* to be motion tolerant. Using data compression techniques, we can transmit by mud pulse telemetry the T_2 distribution in real time from the borehole to the surface. This enables the drilling operator to use the NMR data for real-time decisions such as geosteering.

Keywords

NMR, well logging, while drilling, T_2, low field gradient

1. Introduction to downhole NMR

In oil and gas well logging, nuclear magnetic resonance (NMR) has long been considered to be a non-routine service because of its complex physics, difficult job preparation, and the highly trained people required for data processing and interpretation. It was only used when other measurements failed to give the complete answer. With recent developments in the field of NMR logging while drilling (LWD), more standard applications became feasible. The development of slimhole NMR LWD technology [1] expands the range of applicable hole sizes from 10⅝ in. down to 5¾ in.-diameter holes.

Wireline technology (lowering measuring instruments by a cable into a borehole after drilling) was developed toward high-end applications comprising many options offered by NMR physics. These applications include diffusion characterization and two-dimensional analysis, as well as multiple frequency and multiple wait-time measurements. In contrast to this tendency, the LWD technology that we developed is for everyday applications, vastly simplifying the complicated measurement and processing concepts developed by wireline counterparts.

During an LWD run, the measurements can be displayed in real time by pulsing data from the tool to the surface via mud pulse telemetry. Due to limited telemetry bandwidth, the amount of data must be reduced, which is realized by compressing techniques. From compressed data, the full echo train can be recovered at surface. From the recovered echo train the T_2 distribution as well as the volumetrics (clay-bound water, bulk volume, bulk volume irreducible, free fluid) can be calculated. With the now improved telemetry rates available, real-time data while drilling can be of similar quality compared to memory data that are dumped and processed when the tool is on the surface again. An overview of the T_2 data processing and interpretation is given in Fig. 2. Data compression, transmission and recovery are used for real-time processing only, but are not needed for memory data processing. The excellent quality of the real-time T_2 distribution has been illustrated by a comparison to T_2 distributions from post-processing [1].

2. NMR logging while drilling

NMR-LWD tools are part of the drillstring and need to deal with its strong vibration. Vibration and drilling motion may cause fluctuations of the static magnetic field in the rock formation. In the past it was assumed that, for this reason, for NMR relaxation measurements, only T_1 measurements in the form of saturation recovery were possible to avoid motion artifacts. While the saturation recovery T_1 measurement is indeed motion- tolerant, it is also slow. We, therefore, looked for a faster alternative and found it in the T_2 relaxation measurement, known from wireline NMR and performed by using long echo trains. In this context “long” means at least 1000 echoes. Of special concern in this method is the phase error that can occur between echoes when the static field is unstable. The phase error $\Delta\varphi$ is given by equation (1):

$$\Delta\varphi = \gamma \cdot G \cdot v \cdot \left(\frac{TE}{2}\right)^2 \tag{1}$$

where γ is the gyromagnetic ratio, G the static field gradient in the direction of the movement, v the velocity in the same direction and TE the inter-echo time. Thus to minimize the phase error we need to use an NMR sensor with low static magnetic field gradient G, minimize motion (i.e. v), and use a short inter-echo time TE. The latter is of special concern as it appears quadratic in equation (1).

We achieve the motion reduction by using non-rotating string stabilizers. These stabilizers are especially effective in horizontal boreholes where they reduce the friction between drillstring and borehole wall. In consequence the string rotates quietly with little lateral movement. The NMR sensor configuration is similar to Jackson et al. [2] and Clow et al. [3] but with modification for a drillstring. The static and radiofrequency (RF) magnetic fields are both axisymmetric, which ensures that the NMR tool can rotate as part of the drillstring without influencing the NMR measurement. The radial gradient in the sensitive NMR volume is only 2 to 2.5 Gauss/cm, depending on NMR tool size. Fig. 1 shows the principal arrangement. The third ingredient for motion-artifact-free NMR is a short inter-echo time TE. Reliably, we achieve $TE = 0.6$ ms; but in certain situations even down to $TE = 0.4$ ms is possible. The keys to achieving low TE are the mechanical construction of the NMR sensor and low-noise electronic damping to minimize acoustic and electronic ringing after the RF pulses.

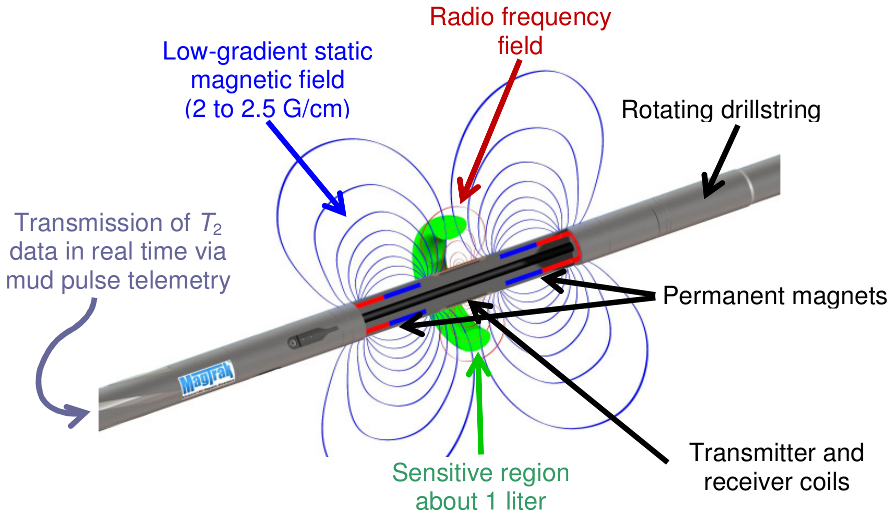


Fig. 1: Illustration of the NMR sensor as part of the drillstring.

The ability to log high quality T_2 data while drilling is validated by an excellent match of while-drilling and relog T_2 data as shown in [4]. Furthermore, comparison of LWD data to wireline data emphasizes the quality of the T_2 data acquired while drilling [5].

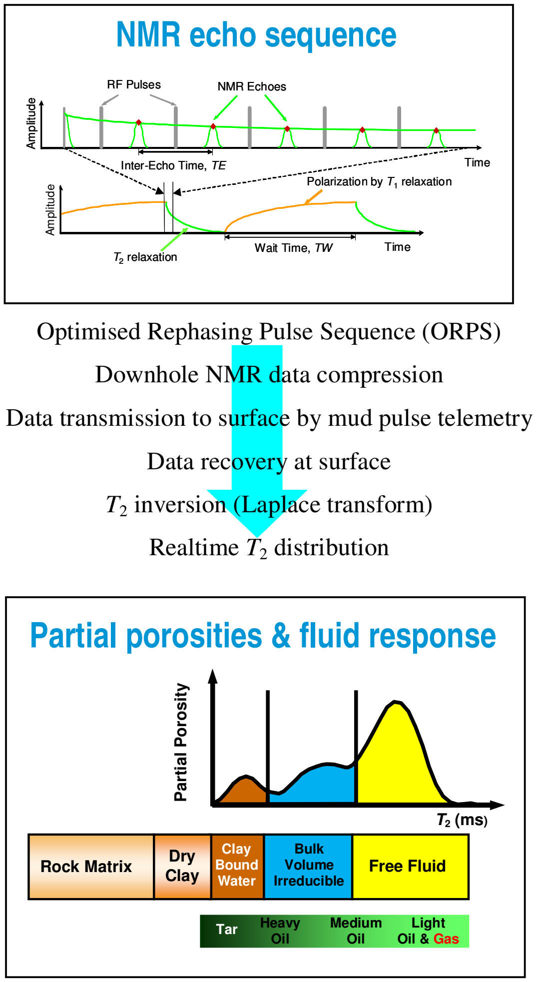
3. Advantages of a small static field gradient

In the previous section, we explained why a small static field gradient enables the acquisition of motion-artifact-free long echo trains. But a small gradient presents a further advantage. The T_2 relaxation (equation (2)) is governed by bulk liquid relaxation, surface relaxation and diffusion:

$$\frac{1}{T_2} = \underbrace{\frac{1}{T_{2,bulk}} + \rho \frac{S}{V}}_{\textit{intrinsic } T_2} + \underbrace{\frac{1}{12}(\gamma\, G\, TE)^2\, D}_{\substack{\textit{relaxation due to} \\ \textit{diffusion}}} \tag{2}$$

where $T_{2,bulk}$ is the bulk T_2 relaxation time of the fluid in the pore, ρ is the surface relaxivity, S and V are surface and volume of the pores and D is the diffusivity of the fluid in the pore.

A small field gradient G and short inter-echo time TE render the diffusion term insignificant, i.e. we are able to measure intrinsic T_2. This simplifies the interpretation of the measured T_2 distribution (for an explanation of T_2 distribution and partial porosities see Fig. 2). Without diffusion effect, T_2 is long in light (low-viscous) oil and gas, allowing us to discriminate these hydrocarbon (HC) fractions from heavier (higher viscosity) oil and water. Our experience shows that light HC quantification is indeed accomplished by a simple T_2 cutoff approach for many applications. Mixed- or oil-wet conditions, only if they substantially shorten the HC $T_{2,}$ pose a limitation to this approach. However, we hardly encountered these conditions in practice so far. Furthermore, a substantial amount of while-drilling runs takes place in horizontal or highly inclined wells where the reservoir is known to contain no movable water. Thus, it is particularly easy to identify the HC volume as the movable fluid volume. This even applies, if mud filtrate invades into the formation, replacing part of the native HC. Invasion, though, is affecting LWD data less than wireline data.



Optimised Rephasing Pulse Sequence (ORPS)
Downhole NMR data compression
Data transmission to surface by mud pulse telemetry
Data recovery at surface
T_2 inversion (Laplace transform)
Realtime T_2 distribution

Fig. 2: The ORPS measurement and the processing steps leading to the real-time partial porosities. ORPS is an echo sequence similar to CPMG but with tipping angles (RF pulse lengths) optimized for inhomogeneous static and RF fields [6].

An example is shown in a while-drilling log from the North Sea, characterizing a chalk reservoir along a horizontal well path (Fig. 3) [7]. Track 1 shows natural gamma ray (GR), borehole size (caliper), and drilling speed (rate of penetration). Track 2 shows the NMR T_2 distribution incl. separation into bound water (BW) and free (i.e. producible) fluids by a T_2 threshold (BW cutoff). Track 3 shows the NMR porosity, incl. separation into free fluid and bound water, compared to neutron porosity and formation density.

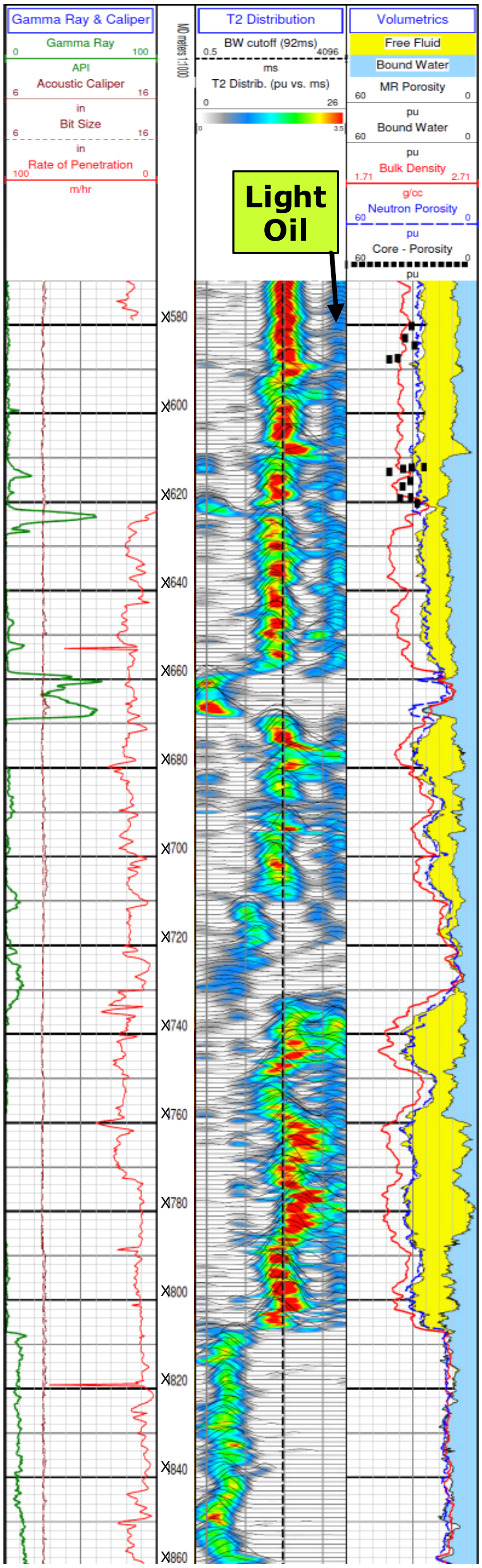


Fig. 3: Log of various LWD measurements in a North Sea Chalk, characterizing the reservoir. For details see text.

Low GR indicates the HC-bearing chalk reservoir sections. High GR indicates tight chalk and shale beds. This corresponds to the T_2 distribution signature and the NMR volumetrics, which show free fluid (i.e. medium to long T_2 components) in the chalk reservoir section but none in the tight chalk and shale beds. NMR provides the unique opportunity to characterize the reservoir quality by separating bound water and producible fluid. This information can also be used to estimate an (uncalibrated) permeability index not shown in the figure.

The light oil, present in the formation, is apparent in the T_2 distribution as a late T_2 peak. This finding is confirmed by the neutron porosity and density data. The porosity from the neutron measurement is proportional to the density of hydrogen atoms (hydrogen index, HI) like the porosity from the NMR measurement. Therefore, both will underestimate porosity for light oil and gas with $HI < 1$. The density measurement reflects the gas density and, therefore, yields low values. This behavior is typically used to identify light oil and gas by a crossover between the density on one hand vs. neutron and NMR on the other hand (i.e. neutron and NMR porosity read low compared to equivalent density porosity) as shown in the log example. During drilling of the well, rock cores were taken to surface and investigated in a lab. The porosity values of the core, without fluid effects, validate the light oil and gas crossover in the log example and confirm the porosities of the different measurements.

Combining the information from all downhole measurements yields an accurate description of the reservoir which is used to assess the commercial viability of a reservoir by critical information such as the amount of producible hydrocarbon, the extension of the reservoir sections, and the expected production performance.

4. Conclusions

NMR technology plays an increasingly important role for hydrocarbon reservoir characterization. With a proper tool design an NMR T_2 measurement can be performed while drilling, independent of drilling motion and vibration. The key elements for the design are mechanical stabilization of the tool, a small magnetic field gradient and a short inter-echo time TE. The small field gradient and short inter-echo time suppress the diffusion effect and, therefore, enable an easy detection and quantification of light oil and gas components in a reservoir.

References

[1] T. Kruspe, H.F. Thern, G. Kurz, M. Blanz, R. Akkurt, S. Ruwaili, D. Seifert, A.F. Al Marsala, Slimhole Application of Magnetic Resonance while Drilling, SPWLA 50th Annual Logging Symposium, The Woodlands, Texas, United States, (2009).

[2] Jackson et al., US patent 4,350,955.

[3] Clow et al., US patent 4,629,986.

[4] Marzorati D., Barbieri E., Thern H. F., Scanavino D., Tilsley-Baker R., Benefield M., Kruspe T., Fischer M., Magnetic Resonance While Drilling for Geosteering and Rock Quality Differentiation, presented at OMC, Ravenna, Italy, March 28-30, 2007.

[5] Akkurt, R., Marsala, A.F., Seifert, D., Al-Harbi, A., Buenrostro, C., Kruspe, T., Thern, H.F., Kurz, G., Blanz, M., and Kroken, A., Collaborative development of a slim LWD NMR tool: from concept to field testing, SPE Saudi Arabia Section Technical Symposium and Exhibition, Al Khobar, Saudi Arabia, 9-11 May, 2009.

[6] Hawkes et al., US patent 6,466,013 B1.

[7] A.K. Thorsen, T. Eiane, H.F. Thern, P. Fristad, S. Williams, Magnetic Resonance in Chalk Horizontal Well Logged With LWD, SPE Res Eval & Eng, **13** (4): 654-666, SPE-115699-PA.