High Resolution Core Logging using Nuclear Magnetic Resonance and Computed Tomography

Petro Babak[1], Sergey Kryuchkov [1,2], Jonathan Bryan [1,2], Apostolos Kantzas [1,2]

(1) University of Calgary

(2) PERM Inc.

Summary

Digital core logging provides important knowledge about the structure and properties of hydrocarbon reservoirs. The goal of core logging is to measure density maps (CT imaging) and profiles of fluid saturations and properties (low field NMR) at a scale that is much finer than what is obtained through logging tool measurements. Digital core logging is based on non-invasive methods to measure these fluid and rock properties, prior to slabbing the core and running routine core analysis on selected sample plugs. Extracting detailed information from these tests is often a challenge due to the differences in the spatial resolutions of acquired measurements. In such case, interpretation of the obtained measurements is often performed at a lower spatial resolution level and leads to loss of valuable information at higher resolutions.

The aim of our work is to propose a methodology for obtaining high resolution digital core analysis based on CT scans and NMR tests. The spatial resolution of CT scans and the corresponding measurements of core porosity is usually very high. On the other hand, the resolution of NMR tests is restricted by the size of the NMR magnet. Therefore, the core saturations, viscosity and permeability obtained from NMR tests reflect the integrated core properties over the length of the NMR magnet. To perform analysis of NMR core logging at the desired small spatial resolution, we developed an efficient downscaling tool for a series of NMR core measurements based on the deconvolution algorithm. It was shown that this algorithm works efficiently for obtaining formation saturations, porosities, and fluid viscosities for real cores. The validation of the developed deconvolution algorithm of liquid saturations and porosities was executed based on the Dean-Stark measurements on core plugs selected along the entire well.

To automate the developed high resolution core logging approach using NMR tests, a computer software has been developed. This software integrates the information about cores obtained at different spatial resolutions, allows obtaining detailed digital core logs and calibrates the digital core logs from NMR and CT with the information obtained from the Dean-Stark and other core analyses.

Introduction

The resolution of NMR measurements depends on the size of the NMR instrument box, Figure 1.

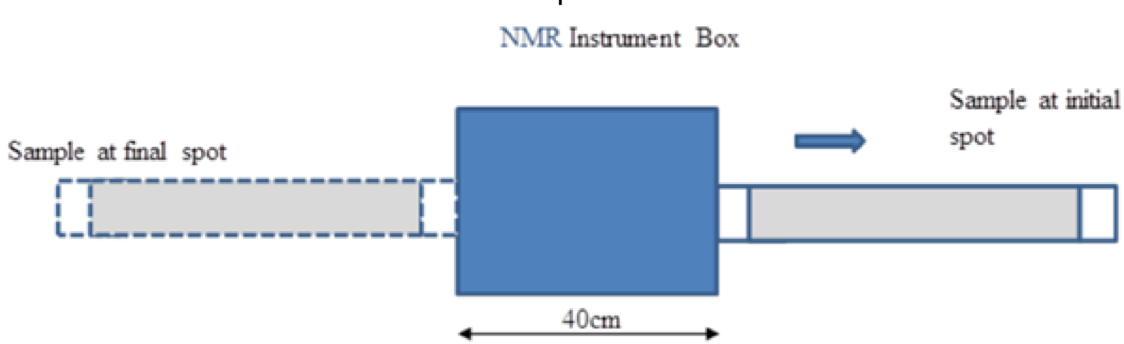

Figure 1. Illustration of NMR measurement process for core logging.

In order to measure full diameter core, the magnet size is large (comparable to the size of a logging tool). As a result, the measured NMR signals from the experiment contain the signals that represent the integrated information over relatively long interval of the core logs. The length of this interval is related to the size of NMR magnet.

Practical applications of core log analysis often require knowledge about the cores with better spatial resolution than it is allowed by the size of NMR magnet. The finer resolution of core analysis is, in particular, important for cores from heterogeneous formations. For heterogeneous formations thin layers of shale might create barriers for fluid flow and significantly diminish well productivity. CT imaging of core already provides a high resolution density map and density profile of the acquired core. The goal of adding high resolution NMR is to evaluate the T_2 distribution of fluids and hopefully extract a similar high frequency profile of fluid saturations within the core.

Theory and/or Method

In order to downscale the NMR information to smaller spatial scale, we need to estimate the nature of signal integration represented by a kernel, $K(x,\delta)$ with the position x ranging over the size of NMR measurement equipment and the spatial resolution δ. The following procedure can be used for estimation of the kernel.

Step 1: Kernel measurements. To estimate the kernel we use pure substance with known T_2 distribution. To provide the downscaling with the resolution δ, we fill a cylinder of the height δ with the selected substance. Then we move the cylinder inside of the NMR measurement box gradually with the lag δ. For each position of the cylinder in the measurement box we take NMR measurement (usually with CPMG sequence), see Figure 2.

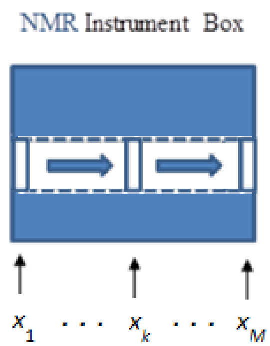

Figure 2. Illustration of Step 1. One or more homogeneous samples are measured at M positions with the resolution δ.

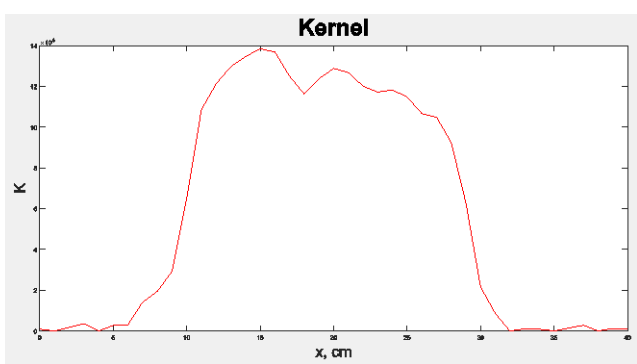

Figure 3. Example of estimated kernel from Step 1 for water sample. The resolution of the kernel is $\delta = 1$ cm. The length of the kernel is $\Delta = 40$ cm. Sweet spot for the kernel contains about 20-23 cm. Outside of this interval the signal is very small.

Kernel estimation can be done by defining the total amplitude of the NMR signals. This operation can be performed based on T_2 NMR inversion of the signals for each position of the substance in the equipment. Figure 3 illustrates the processed kernel.

Step 2: Core measurements. Actual core measurements and interpretation. Each core is moving gradually into NMR Instrument box with the space lag δ. At each position x_k an NMR measurements are taken, k=1,…,*N*+*M*+1. Typically it is CPMG sequence. For consistency of NMR interpretations, the measurements at all positions are taken with the same parameters. Number of NMR scans is equal to $N + M - 1$, where N is the number of positions along the core, and M is the length of the kernel.

After all core is scanned in NMR Instrument tool box, NMR sequences are processes to define the distribution of the relaxation time. The NMR sequence inversions are performed with the same smoothing parameters as with our in-house software.

Step 3: Downscaling of core processed information. To downscale the integrated NMR relaxation time information collected in Step 2, we will solve the overdetermined system of equations using approximation techniques based on the least square nonnegative algorithm, see Mitchell et al. (2012).

Examples

The following example is presented to illustrate the downscaling algorithm. Figure 3 shows the kernel measured for 1cm water cylinder moved gradually into the NMR instrument with 1cm lag. The core of length 76 cm was moved into the NMR instrument with lag 1cm and for each position in the instrument the weighted average T_2 distribution over the length of the NMR instrument is estimated. As it shown in Figure 4, there are 116 measurements were performed for the given core (116=76+41-1). The top plot shows one cross section for one location of the core in the instrument from all T_2 distributions for all core.

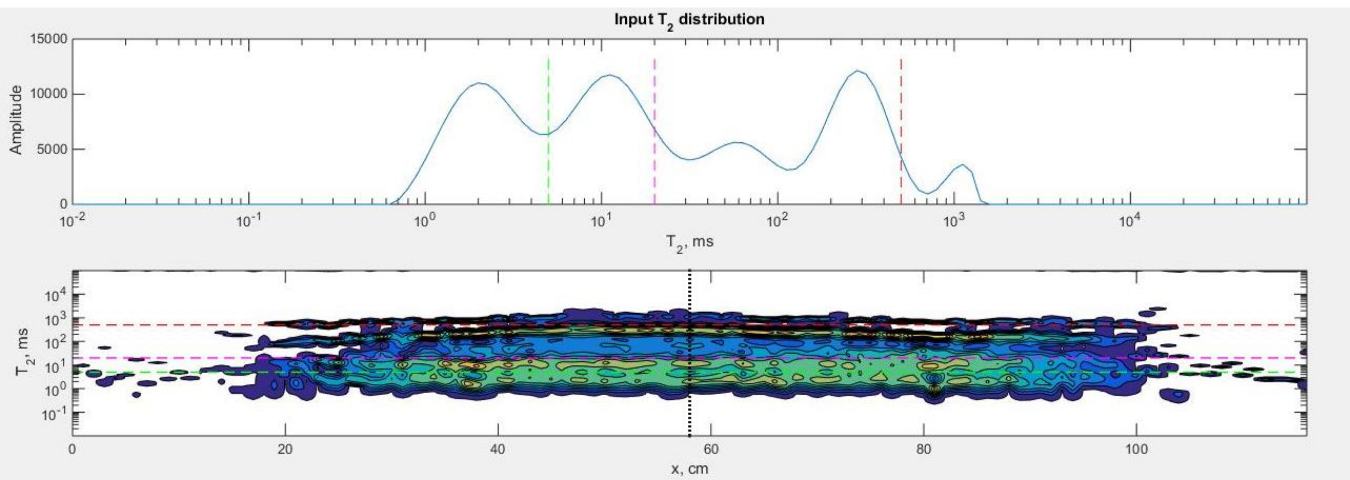

Figure 4. T_2 distribution along the core measured using NMR instrument with kernel of length 40cm shown in Figure 3. The top panel shows T_2 distribution for one position of the core in the NMR instrument. The bottom panel presents T_2 distributions for all positions in the NMR instrument.

Figure 5 illustrates the downscaling of the NMR distributions along the core for the space resolution 1cm. The downscaling was obtained by solving the regularized nonnegative least square problem (7). The downscaled NMR distribution is shown for the length of the core 76cm.

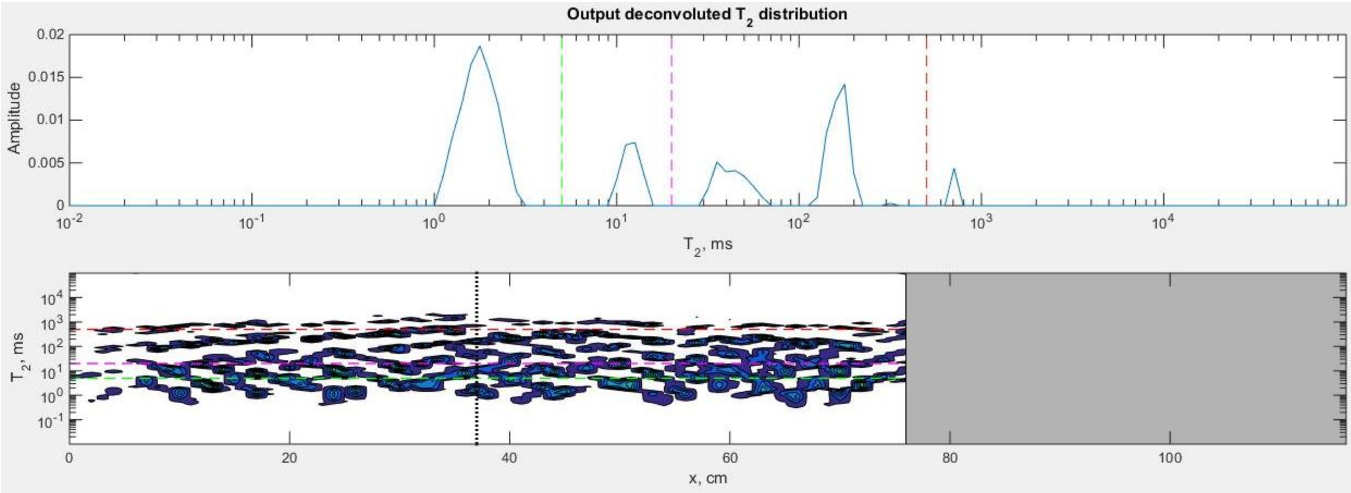

Figure 5. Downscaled T_2 distribution along the core. The top panel shows T_2 distribution for one position along the core. The bottom panel presents T_2 distributions for all positions along the core.

Figure 6 shows the estimated detailed water saturation log along the core calculated based on the T_2 distributions presented in Figures 4 and 5 with constant T_2 water cut-off.

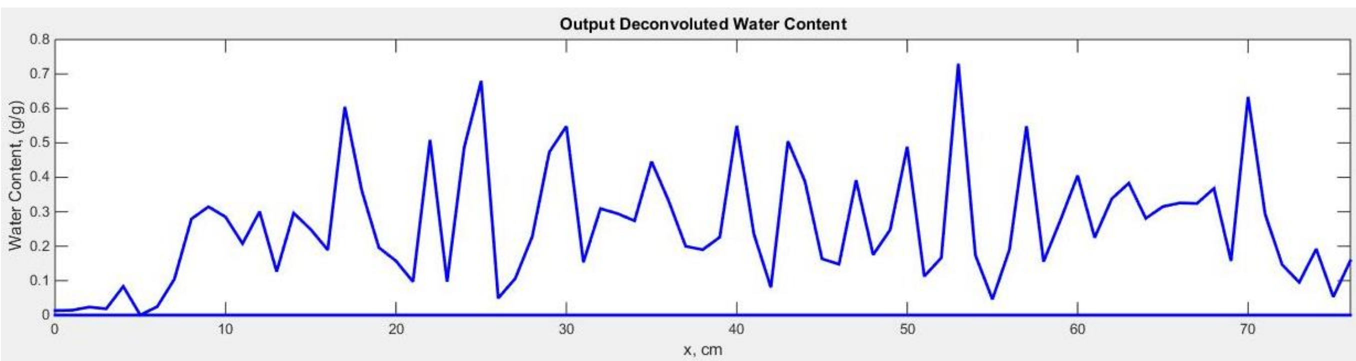

Figure 6. Estimated detailed water saturation log after downscaling process.

Conclusions

In this work we present the methodology for obtaining detailed core information from NMR tests. Downscaling of the NMR information was achieved from the data with 40 cm to 1 cm precision.

References

Mitchell, J., Chandrasekera, T.C., Gladden, L.F. Numerical estimation of relaxation and diffusion distributions in two dimensions. Progress in Nuclear Magnetic Resonance Spectroscopy 62 (2012), 34-50.