HSR-NMR Scanner for High-Throughput Measurement of Fluids Distribution in Whole Cores

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Abstract. Core retrieval, preservation, and analysis provide direct evidence on the presence, quantity, distribution, and deliverability of hydrocarbons of a reservoir. Currently, very little information on the included fluids is measured from the extracted whole cores before they undergo destructive procedure such as slabbing and plugging. Here we present a high-throughput measurement technology, high-spatial-resolution nuclear magnetic resonance (HSR-NMR) Scanner, which measures hydrocarbon and water distribution in whole cores. The HSR-NMR Scanner synchronizes NMR data acquisition with controlled stepwise motion of the whole core through the sensor with the step equal to the desired resolution, deconvolves the acquired NMR relaxation data to obtain HSR fluid distribution in the whole cores. The method overcomes the intrinsic axial averaging of the NMR sensor of a finite length, thereby improving the spatial resolution of measurements. The HSR-NMR Scanner is a high-throughput non-destructive and non-invasive measurement technology. It can measure 3-foot sample in about 70 minutes and provides high-resolution continuous fluid distribution in the whole cores. The HSR-NMR Scanner is especially useful for unconventional source rock whole cores where mud invasion is minimum and majority in situ fluids remain in the cores. This scanning technology represents a significant advancement over current industry standard practices in obtaining fluid information from whole cores, which generally are destructive, expensive, and time consuming while only providing sporadic data in the whole cores where plugs or subsamples were taken.

1 Introduction

Cores are routinely extracted from subsurface reservoirs for laboratory study, providing direct evidence and data on the presence, quantity, distribution, and deliverability of hydrocarbons of the reservoirs. Petroleum industry has developed many optimized practices in core measurements for conventional sandstone and carbonate reservoirs [1]. In recent decades, new core measurement techniques have emerged alongside the rapid development of unconventional source rock reservoirs [2]. Drilling subsurface cores is expensive, yet limited information is obtained from the whole cores before they undergo destructive processes such as slabbing, plugging, and for unconventional source rocks, crushing [2]. In addition, majority core analysis methods are invasive: *in situ* fluids are extracted, rock samples are cleaned and dried, and external fluids may be introduced [1]. As a result, the sample may be altered by the analysis method and the measured sample properties may be incorrect. A non-invasive method for core analysis is preferred to obtain sample properties.

Reservoirs can exhibit significant variations in properties such as porosity, fluid saturation, and permeability which influence the distribution and flow of hydrocarbons. Accurately determining reservoir heterogeneity is crucial in the petroleum industry as it directly impacts the efficiency and effectiveness of hydrocarbon extraction. Knowing these heterogeneities allows for better prediction of reservoir behavior, optimizing drilling and production strategies, and minimizing risks associated with unexpected reservoir conditions. Additionally, understanding reservoir heterogeneity helps in predicting the performance of enhanced oil recovery techniques and in making informed decisions about reservoir development and management. Therefore, accurate determination of reservoir heterogeneity is essential for maximizing the economic and operational success of petroleum extraction projects. Quantitative core analysis in the petroleum industry mainly uses inch-scale plugs [1]. Typically, plugs are taken at one depth every foot of core, with a few additional depths at the most interesting reservoir sections. This results in sparse data, which may significantly underestimate reservoir heterogeneity.

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Here we present the high-spatial-resolution (HSR) nuclear-magnetic-resonance (NMR) Scanner technology. It directly scans the whole cores and is a noninvasive and non-damaging method. Equally important, it provides continuous fluid distribution at inch scale and thus able to capture the full reservoir heterogeneity. The HSR-NMR Scanner was developed and tested for high-throughput measurement, capable of measuring a 3 ft core in approximately one hour.

2 Method

The concept and a pilot testing of HSR-NMR method were presented previously [3, 4]. Here, we provide an updated method description with mathematical format more suited for software coding in the developed HSR-NMR Scanner.

2.1 System definition

Conventional NMR spectrometer is problematic in measuring a long sample (a typical whole core is one to three ft or one m) with a short helical NMR sensor (typically about 3 inches long), as illustrated in Fig. **1**. For a traditional NMR instrument, the spatial resolution cannot be better than the finite NMR sensor length or the diameter of the core, whichever is greater. Also, the finite length of NMR sensor generates an inhomogeneous magnetic field, especially at the ends of the coil, as illustrated by the purple vectors in Fig. **1**. Therefore, the measured signal intensity at the ends is different from that of in the middle. As a result, the routine NMR experiments cannot provide accurate evaluation of the fluid of a long sample if the sample is heterogeneous.

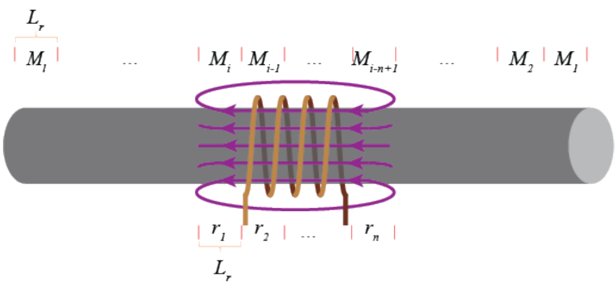

Fig. 1. Schematic illustration of a long rock sample (black cylinder) in a solenoid NMR sensor (yellow wires). The coil generates a magnetic field, relatively homogeneous inside the coil and significantly inhomogeneous on the ends, shown as purple lines. The NMR signals of the rock $[\boldsymbol{M_1}, \boldsymbol{M_2}, \cdots, \boldsymbol{M_l}]$ is shown as a distribution along the core axial direction with each value $\boldsymbol{M_i}$ $(i = 1, \ldots, l)$ representing the NMR signal from the total fluid of a desired length of spatial resolution L_r. The overall measurement sensitivity of the NMR sensor is shown as a 1D response map $[r_1, r_2, \cdots, r_n]$ along the axis with the same spatial resolution L_r.

A method was proposed and tested to overcome these challenges to provide HSR measurement for long samples [3, 4]. In the method, a desired spatial resolution, L_r, is predetermined and can be much smaller than the NMR sensor length. The same length factor L_r is also used to characterize the response map of the NMR sensor, as depicted in Fig. **1**. The NMR signals of the rock $[\boldsymbol{M_1}, \boldsymbol{M_2}, \cdots, \boldsymbol{M_l}]$ is shown as a distribution along the rock axis with each value $\boldsymbol{M_i}$ $(i = 1, \ldots, l)$ representing the NMR signal from the rock fluids at the desired spatial resolution L_r. The axial response of the NMR sensor is summarized as a response map $[r_1, r_2, \cdots, r_n]$ [3].

2.2 Data acquisition method for HSR-NMR

The data is acquired step-wisely by moving the whole core sample through the NMR sensor with the step size equal to the desired resolution, as illustrated in Fig. **2**. Specifically, a series of data acquisitions are carried out, beginning with the top of the core against the start of the sensitive window of the *r.f.* probe. This way, the initial scan should always be a largely noise signal. NMR acquisitions are continued along the length of the core by moving it through the NMR sensor at the desired resolution, L_r. The acquisition continues until the core completely passes through the sensitive window, once again resulting in a signal which is largely noise. Fig. **2** also includes the detected NMR signal as a result of the sample fluid distribution and its position in the NMR sensor at each step.

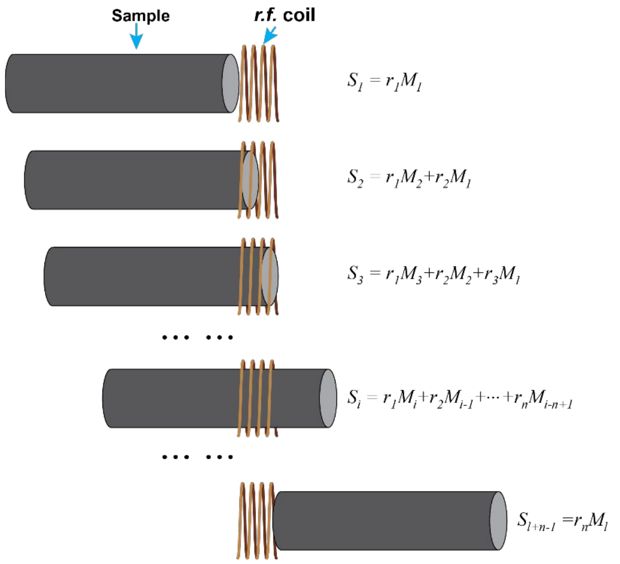

Fig. 2. Illustration of step by step moving the sample through the NMR sensor and the detected NMR signal.

The NMR signal acquired at step *i* when moving the sample through the NMR coil can be expressed as

$$\boldsymbol{s_i} = r_1\boldsymbol{M_i} + r_2\boldsymbol{M_{i-1}} + \cdots + r_n\boldsymbol{M_{i-n+1}}, \qquad (1)$$

in which $[s_1, s_2, \cdots s_m]$ is the matrix of NMR signals acquired by the NMR sensor and *m* is the total steps that the sample moves from one end of the coil to the other end. Again, $[r_1, r_2, \cdots, r_n]$ is the response map, where *n* is the number of points of the response map; $[\boldsymbol{M_1}, \boldsymbol{M_2}, \cdots, \boldsymbol{M_l}]$ is the HSR distribution of NMR signal of the rock representing the fluids distribution in the sample of each point we want to obtain from the measurement. Note that here the spatial resolution is the same for the fluid distribution and for the response map. For optimized measurement, we should make sure: $m \geq l + n - 1$. When $m > l + n - 1$, the acquired NMR data includes situations where the sample is completely outside of the NMR sensor and therefore the acquired data only contains noise.

The NMR signal for fluids in a rock sample is typically measured using the CPMG method [5, 6]. The measured NMR signal is a full CPMG echo-train containing j number of datapoints at each measurement. Thus, the measured signal $\boldsymbol{S}$ can be written as a matrix

$$\boldsymbol{S} = \begin{bmatrix} s_{1,1} & \cdots & s_{1,j} \\ \vdots & \ddots & \vdots \\ s_{m,1} & \cdots & s_{m,j} \end{bmatrix} \tag{2}$$

2.3 Data processing for HSR-NMR

2.3.1 Deconvolution to obtain HSR-NMR echo-trains

Similar to measured echo-trains $\boldsymbol{S}$, the HSR-NMR echo-train $\boldsymbol{M}$ can be written as

$$\boldsymbol{M} = \begin{bmatrix} \boldsymbol{M_{1,1}} & \cdots & \boldsymbol{M_{1,j}} \\ \vdots & \ddots & \vdots \\ \boldsymbol{M_{l,1}} & \cdots & \boldsymbol{M_{l,j}} \end{bmatrix} \tag{3}$$

Each row in $\boldsymbol{M}$ is an echo-train we want to obtain that truly represents the NMR signal of the fluid in the rock at high spatial resolution.

Eq. (1) can be written in a simple matrix form as

$$\boldsymbol{S} = \boldsymbol{RM} \tag{4}$$

with

$$\boldsymbol{R} = \begin{bmatrix} r_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ r_2 & r_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ r_3 & r_2 & r_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ & & & \ddots & & & & & & & & & & \\ 0 & 0 & 0 & 0 & r_n & \cdots & r_3 & r_2 & r_1 & 0 & 0 & 0 & 0 & 0 \\ & & & & & & & & & \ddots & & & & \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & r_n & r_{n-1} & r_{n-2} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & r_n & r_{n-1} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & r_n \end{bmatrix} \tag{5}$$

Note that the dimensions of $\boldsymbol{S}$, $\boldsymbol{R}$, and $\boldsymbol{M}$ are $m \times j$, $n \times m$, and $l \times j$, respectively.

Estimation of NMR fluid distribution represented by the matrix $\boldsymbol{M}$ from the measured data $\boldsymbol{S}$ from Eq. (4) is an inversion problem. Due to the minimum data requirement, $m \geq l + n - 1$, Eq. (2) is an over-determined system. In order to obtain reliable information of the fluid content from the noisy data and mitigate the impacts from the end effects of the measured data, we adopted Iterative Reweighted Least Square (IRLS) approach [7, 8]. IRLS estimates $\boldsymbol{M}$ from the measured data $\boldsymbol{S}$ by minimizing the following misfit function:

$$\underset{A}{min} \frac{1}{p} \|\boldsymbol{RM} - \boldsymbol{S}\|^p \tag{6}$$

where p is a predefined constant with values in [1, 2]. The impact of S on the solution of function (6) varies with the choice of p. A computation program was written in Matlab to carry out this calculation. The obtained results - eliminate the end effects of the NMR sensor and have the desired high spatial resolution.

2.3.2 Inversion of the echo trains for T_2 spectra

One further inversion was then used on the echo trains $M_{i,j}$ $(j = 1, \cdots, m)$ to obtain the NMR T_2 spectrum. This was done using an established inversion method such as CONTIN [9, 10].

2.4 HSR-NMR Scanner

An HSR-NMR Scanner for high-throughput core scanning was built, as shown in Fig. **3**. The 110 mm borehole allows scanning of 4-inch diameter whole cores. The length of sample convey was built to scan cores of 3 ft or shorter. Slightly longer cores such as 1 m can be scanned as well.

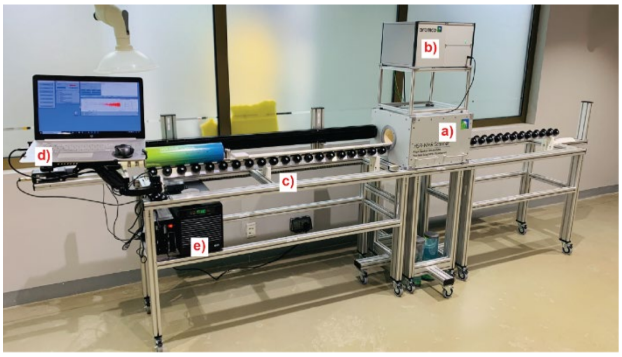

Fig. 3. 2 MHz whole core HSR-NMR Scanner for high-throughput core scanning. a) the magnet with a borehole size of 110 mm and an NMR sensor at the center; b) the *r.f.* control system; c) sample conveyer; d) computer controlling NMR pulse sequences, data acquisition and processing, and core moving; e) Uninterruptible Power Supply.

2.4.1 The response map of NMR sensor *of the HSR-NMR Scanner*

The 1D response map of the NMR sensor along its axial direction of the HSR-NMR Scanner, as shown in Fig. **4**a, was measured using a cylindrical disk made with polycarbonate glass filled with CuSO4 doped water at 1000 ppm, as shown in Fig. **4**b. The enclosed water in the standard sample is also in cylindrical shape with width 0.25 inch and diameter 3.75 inches. The T_1 and T_2 of the doped water are approximately 100 ms.

The response map of the NMR sensor was measured from the acquired NMR signal intensities by moving the standard sample through the instrument step-by-step with 0.25 inches step. The diamonds in Fig. **4** shows the measured 1D response map of the NMR sensor at 0.25 inches spatial resolution. The response map indicates that the homogeneous region of the NMR sensor of the HSR-NMR Scanner is about 3 inches. Outside this homogeneous region, the detection sensitivity falls at both ends of the coil but overall, approximately a 6 inches section contributes to the detected signal. In this spectrometer, obviously, a sample longer than 3 inches extends out of the homogeneous zone of the NMR sensor and cannot be easily quantified, especially for heterogenous samples such as rocks.

If larger spatial resolution is desired, the response map was obtained by taking average of the measured response map at 0.25 inches. For example, for 1-inch spatial resolution, the response map is obtained by taking average of every 4 points, as the red triangles in Fig. **4**.

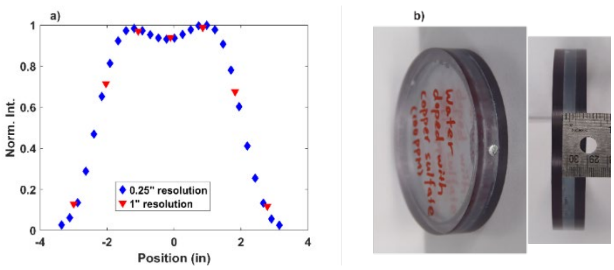

Fig. 4. a) measured response map of NMR sensor of the HSR-NMR Scanner for 0.25 inches in blue diamonds and one inch in red triangles resolution, respectively; b) the specially made standard cylindrical sample used to map the axis response of the NMR sensor, shown from different angles.

3 Results and discussion

3.1 Acquired and processed data

Fig. **5** shows an example of data acquisition and processing workflow of the HSR-NMR Scanner using a whole core of 8 inches in length and 4 inches in diameter. To make sure no signal is lost, the HSR-NMR Scanner acquires some data even when the core is completely outside the NMR sensor. As a result, the acquired CPMG echoes are zeros at the two ends, as shown in Fig. **5**a. These zero signals at the two ends were automatically removed by the instrument software. The remaining CPMG echoes form the data matrix $\boldsymbol{S}$ in Eq. (2), shown in Fig. **5**b, were used as input for deconvolution to obtain the HSR-NMR CPMG echoes $\boldsymbol{M}$ in Eq. (3), shown in Fig. **5**c. Each CPMG echo train in Fig. **5**c was then inverted to generate the HSR-NMR T_2 spectrum, shown in Fig. **5**d. It is noteworthy to repeat here that each CPMG echo train in Fig. **5**a and **5**b are from a section about 6 inches (i.e. before deconvolution) in length of the whole core, while each CPMG echo train in Fig. **5**c and each T_2 spectrum in **5**d are from only one inch section of the whole core and thus represent the desired HSR results.

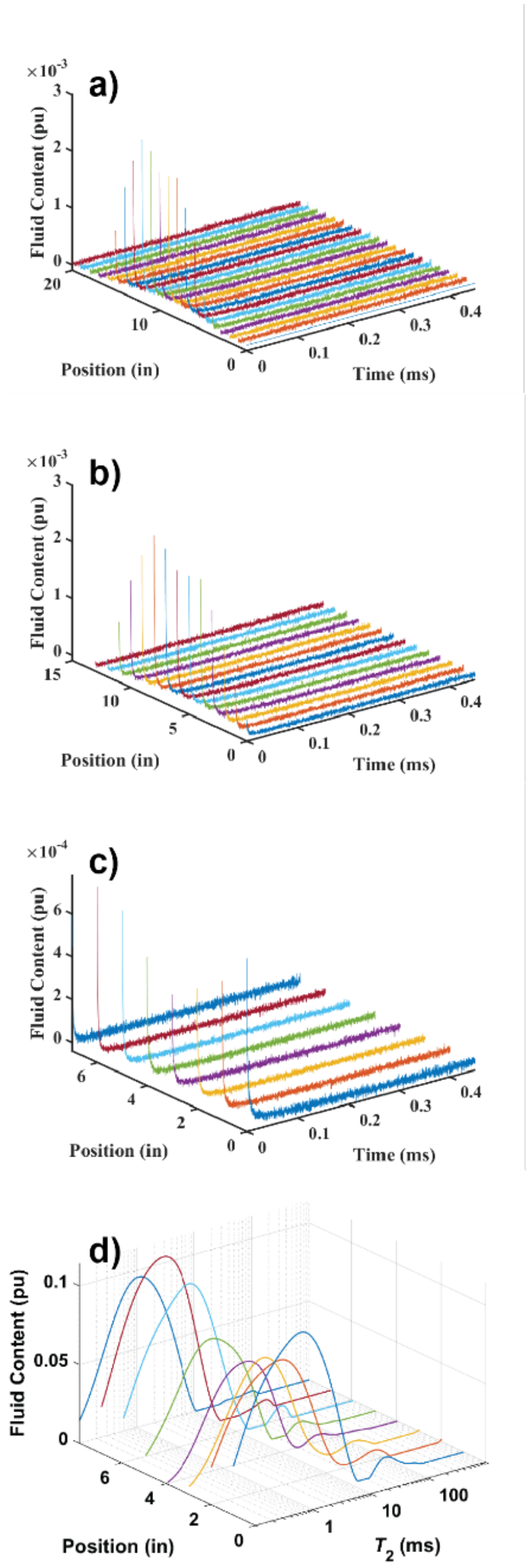

Fig. 5. Illustration of data acquisition and processing workflow for HSR-NMR Scanner using an 8 inches long whole core: a) all acquired CPMG echoes when the core moves through the scanner at a step of 1 inch including zero signals when the sample is completely outside of the NMR sensor; b) CPMG echoes used for deconvolution by trimming the acquired zero signals at the two ends in a) from the system software; c) HSR-NMR CPMG echoes after the deconvolution, d) HSR-NMR T_2 spectra of the sample with each spectrum representing the T_2 of one-inch section of the whole core.

3.2 Sensitivity and accuracy of the HSR-NMR Scanner

In NMR experiments, a higher signal-to-noise ratio (SNR) leads to more precise data processing in deconvolution and inversion and consequently more accurate results. A higher SNR requires more accumulation of scans, resulting in an increased overall experimental time. It is always important in NMR experiments to strike a balance between acquiring data with sufficiently large SNR for accuracy and an appropriate number of scans to minimize the experimental time, especially using HSR-NMR Scanner on a large quantity of cores. Fig. **6** shows results of the acquired, (a) and (c), and inverted HSR-NMR echoes, (b) and (d), for 16 and 4 scans, respectively, for a source rock whole core of 8.5 inches long. It is easy to see those echoes in (a) and (b) have a much larger SNR than those in (c) and (d). However, the measurement porosities of the whole core using the two different number of scans are approximately the same, as shown in (e). The porosities of the whole core ranges from 2.8 to 6.1 pu. This shows that 4 scans are sufficient for this HSR-NMR Scanner to acquire accurate results even for porosity at about 3 pu.

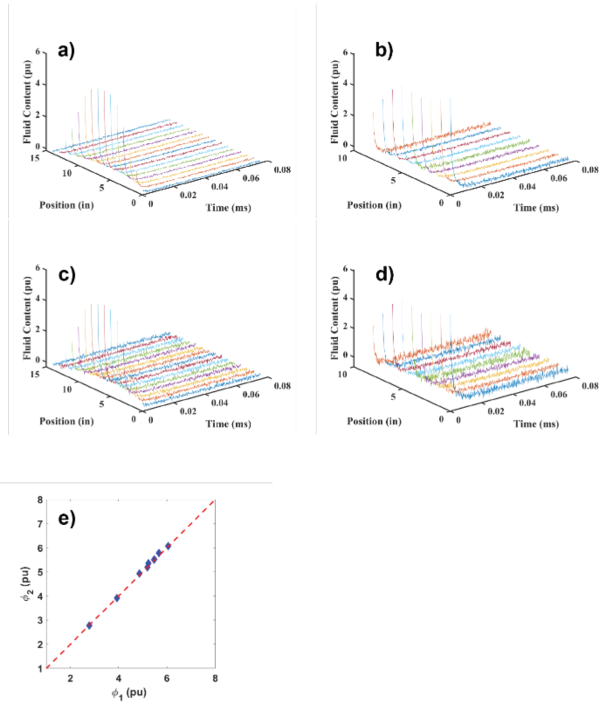

Fig. 6. Effects of data accumulation on the HSR-NMR measurement results: a) acquired CPMG echoes with 16 scans; b) deconvolved HSR-NMR echoes from a); c) acquired CPMG echoes with 4 scans, d) deconvolved HSR-NMR echoes from c); e) cross-plot of HSR-NMR porosity acquired with 16 (ϕ_1) and 4 (ϕ_2) scans.

To further evaluate the measurement accuracy of the HSR-NMR Scanner, whole cores were first measured for fluid distribution and fluid-filled porosity. Plug was then drilled from the whole core and its liquid content was then measured to compare with the HSR-NMR results. Fig. **7** shows such an example. A source rock whole cores of 9 inches long (7a) was measured using the HSR-NMR Scanner. The liquid distribution along the core is shown in 7b. A one-inch diameter plug was taken at 3 inches from the top of the whole core as shown in 7c. The liquid content in the plug was measured to be 7.5 pu, consistent with the results from the measured fluid of 7.4 pu in the whole core before plugging.

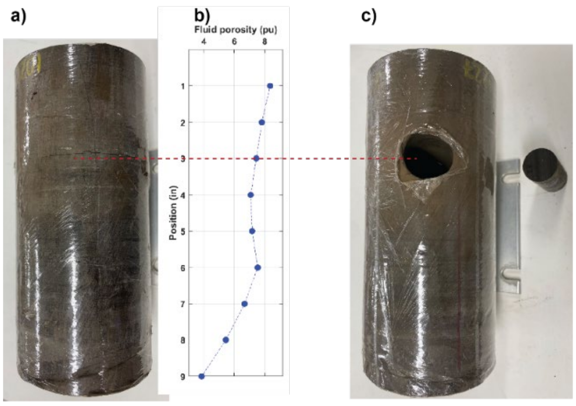

Fig. 7. Testing accuracy of HSR-NMR measurement: a) whole core, b) fluid content measured by HSR-NMR method, c) core carcass and plug.

3.3 Example of high-throughput HSR-NMR measurement

Fig. 8 shows the measurement results from the HSR-NMR Scanner for a composite rock that is 36 inches in length and 4 inches in diameter. The spatial resolution was set to one inch. Figure 8a shows the composite sample of 6 shale rocks of varying lengths and origins: the two lighter-coloured ones are outcrops, while the four darker ones are from the same source rock reservoir but different wells. Fig. 8b displays the fluid distribution measured, with each point representing the total fluid in a 1-inch section of the rock. Figure 8c presents the HSR-NMR T_2 spectra of the core at one inch resolution. The results reveal significant heterogeneity at the inch scale for the reservoir rocks and show minimal fluid content in the two outcrop samples, as expected.

The HSR-NMR Scanner provides continuous, high-resolution data on the samples. The results presented in Fig. **8** were acquired in 72 minutes for the 3 ft core, with acquisition parameter at each step: τ = 75 ms, 4 scans, 1000 CPMG echoes, and interscan delay of 2 s. For different cores, acquisition parameters for scanning needs to be optimized. But the overall time should not significantly different. At this measurement rate, scanning a whole core section of 200 ft takes about three days with only one HSR-NMR Scanner. It delivers continuous fluid distribution at a resolution of one inch, capturing the heterogeneity of the reservoir section.

The HSR-NMR Scanner is a high-throughput, noninvasive measurement tool. It represents a significant improvement upon current industry methods, particularly for unconventional source rock with nD-range permeability, where measuring fluid content is challenging and time-consuming. Current standard practice in the petroleum industry for the source rocks uses GRI method [2]. It involves crushing a rock sample of about 300 g into small particles and then using multiple methods and steps to extract the enclosed fluids for quantification [2]. The GRI method is destructive and requires several weeks to finish. Therefore, using GRI to obtain the fluid HSR distribution in whole cores is cost prohibitive. Generally, only a few sections of the whole core are selected for GRI measurement. The overall data is sparse and could misrepresent some important sections of the reservoir.

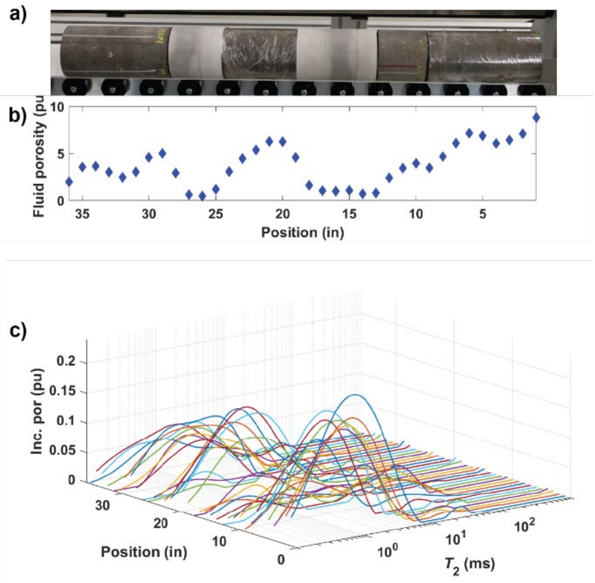

Fig. 8. High-throughput HSR-NMR measurement example. a) a 3-ft composite whole core; b) measured fluid distribution along the core in one-inch spatial resolution; c) the HSR-NMR T_2 spectra with each one representing the total fluids in one inch section of the sample.

It is worth noting that the HSR-NMR Scanner can be easily adapted for wellsite use, enabling immediate scanning of whole cores post-extraction.

4 Conclusion

We have presented an HSR-NMR method to analyze the fluids in large rock samples. The method overcomes the spatial resolution problem caused by the finite response length of the *r.f.* detection coil and obtained HSR-NMR data with spatial resolution much smaller than the spatial response length of the coil. The method can achieve a desired spatial resolution and is not limited by the short relaxation time of the fluid in the rock. Therefore, it can be used to study a variety of reservoir rocks.

Using this non-destructive method, we measured the fluid distributions at one-inch spatial resolution in 23 preserved whole cores from four wells of a source rock reservoir. The measured fluid from the NMR method matches well with the fluid content from GRI method on the same sections of the preserved cores. In addition, the measured fluid distribution correlates well with the kerogen content along the cores when there is obvious lamination in the samples.

The measured results also demonstrated that the HSR-NMR measurement of preserved cores can provide critical information about the heterogeneity or lamination of the reservoir. For the studied source rock reservoir, the preserved cores showed large heterogeneity/lamination in different scales for different regions.

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