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Revolutionizing Reservoir Management: Real-time Petrophysical Analysis with NMR Technology of Drill Cuttings

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ABSTRACT

The ability to predict in real-time subsurface formation properties during the drilling process has been many times documented as being critical to high performance drilling activities. Lowering the costs of geothermal wells could benefit of real time formation properties prediction. Machine learning and AI are generally successful in formation properties prediction if relevant data for training purposes exists. A combination of real time measurements and machine learning could reduce the number of physical experiments while the real time obtained data will improve the accuracy of machine learning prediction. This paper is showing the development of a testing protocol using NMR that could provide relevant data for machine learning future applications. Nuclear Magnetic Resonance (NMR) technology can be used for the measurement of petrophysical properties of reservoirs using drill cuttings. NMR provides a non-destructive and efficient method for analyzing the properties of rock formations, which can aid in reservoir characterization, well placement, and production optimization. Traditionally, petrophysical analysis of reservoirs has relied on core samples, which can be costly and time-consuming to acquire.

On the other hand, cuttings can be utilized for petrophysical analysis, which are small rock fragments generated during drilling operations and are readily available. Hence, the utilization of NMR technology with cuttings presents a valuable opportunity to gather crucial data without the need of core analysis. In this paper, we present results on porosity measurements on artificially generated cuttings from sandstone and limestone blocks in the range of 0.5 – 2mm. NMR porosity using T_1 and T_2 relaxation times of the cuttings as well as their core, were measured and compared in varying conditions- 100% saturated and dry. The results show that as the cutting size increases, the porosity value becomes closer to the cores. Among the samples considered in this work, the results obtained for sandstone, followed the trend more closely. Furthermore, in order to simulate well site conditions, cuttings corresponding to mesh 10 and 35 dimensions (0.5 - 2 mm) were analyzed in different states: excess solution, no excess solution, 24 – 96 hours dry. An inverse relationship was observed between porosity and drying time, and as anticipated, the larger cuttings gave results more closely related to the cores. Overall, the results demonstrate the potential of the application of NMR technology in measuring petrophysical properties of rocks using drill cuttings in real-time. This can be made possible by utilizing the result trends and developing predictive models that consider cutting size, drying time, and other relevant factors. The ability to rapidly assess porosity with NMR technology using cuttings offers a cost-effective and time-efficient alternative to traditional core analysis methods. Ultimately, harnessing NMR technology with drill cuttings has the potential to revolutionize how we gather essential data for reservoir management, leading to more informed decision-making in the energy industry.

1. INTRODUCTION

To obtain accurate measurements of petrophysical data which are essential for understanding reservoirs, a series of measurements have been used in the oil and gas industry. However, all of these measurement techniques have their pros and cons. For example, core measurements give a direct indication of the formation properties, but the coring process is quite expensive and time-consuming. To obtain cores, a special bit and core barrels must be lowered into the well to collect samples. Several trips may be required to collect enough cores from the reservoir sections of a well. During this process, drilling must be done at a slower rate than usual, this makes the coring job cost-intensive (Siddiqui et al. 2005). Moreover, core operational difficulties and the risk of stuck pipe make it near impossible to retrieve cores from horizontal wells. Core recovery from unconsolidated or weaker reservoirs is poor, and some samples' damage can occur during transportation and storage (Siddiqui et al. 2005).

Whereas Measurement-while-drilling (MWD) and logging-while-drilling (LWD) techniques give real-time data that can be used for formation evaluation. Using these techniques, reservoir performance may be predicted, and the reservoir can be better understood. Though logging while drilling gives continuous measurements, however, these measurements are often indirect and use the interpretation of the logs to calculate the formation properties (Santarelli et al. 1998). Moreover, the MWD and LWD techniques have a lower data density due to the time lag caused by the mud telemetry technique used to transfer the data from the bottom hole to the surface (Siddiqui et al. 2005).

On the other hand, drill cuttings, which are rock fragments generated during the drilling process and transported to the surface, are readily available as drilling fluid is circulated throughout the borehole. The cutting size ranges from sub-micron to a few millimeters in diameter and can be used to obtain petrophysical measurements at the well site (Hübner 2014). The use of drill cuttings at any phase of reservoir development for quantitative measurements of reservoir properties provides a cost-effective method as compared to the coring techniques (Althaus et al. 2019). Moreover, the fast-paced nature of drilling operations makes it necessary to obtain real-time data that cannot be delivered from traditional methods such as coring (Kesserwan et al. 2017).

This study aims to ascertain the prospects of reliably measuring porosity using NMR technology on drill cutting and to establish testing protocols to evaluate porosity using NMR technology using drill cuttings that will simulate field conditions that could provide relevant data for machine learning future applications.

2. METHODOLOGY

Nuclear magnetic resonance (NMR) has been a major tool in the oil and gas industry for measuring petrophysical properties such as porosity and density of formation from drill cuttings samples (Chen et al. 2022). The principle behind the technology is based on the measurement of relaxation signals due to the nuclear spin of protons present in fluid saturated geological rocks (Lawal et al. 2020). NMR measurement examines the magnetization of the proton produced when oil or water contained samples are put in a magnetic field. The two essential parameters to describe the magnetization intensity are the longitudinal relaxation time (T_1) and the transverse relaxation time (T_2). T_1 defines the intensity of magnetization in the direction of the static magnetic field, and T_2 defines the intensity of magnetization in the plane perpendicular to the static magnetic field (Weimin et al. 1998).

In a liquid-saturated porous material, the total NMR signal amplitude is directly proportional to the liquid volume and is called the pore volume. The bulk volume of a sample is determined by the outer measurement of a core plug prepared as a right cylinder. Combining the bulk and pore volumes gives the porosity in petrophysical porosity units (Mitchell et al. 2019). Additional petrophysical properties can be determined from the longitudinal and transverse spin relaxation times. A one-dimensional relaxation time distribution is considered an indicator of the pore size distribution. The relationship between the one-dimensional relaxation time and the pore size distribution arises from the fact that the relaxation time of a particle within a pore depends on the size of the pore it is moving through, and by analyzing the distribution of relaxation times, information about the corresponding pore size distribution can be inferred (Allen et al. 1997).

The methodology below outlines the procedure for measuring porosity using Nuclear Magnetic Resonance (NMR) technology applied to cores and artificial cuttings. The methodology covers the preparation and sorting steps necessary for accurate measurements. The work done in this stage involved using two different rock samples – Sandstone and Chalk. The porosity of both the resulting cores and cuttings were measured and compared. Furthermore, the porosity of Limestone artificial cuttings was measured repeatedly to establish consistency of the results obtained using NMR.

2.1 Sample preparation for cores

In this work, 8 core samples (six Sandstones and two Chalks) were obtained from their respective rock beds. Cores from a Bandera Sandstone (4 in total) were obtained from the block. Two of them with vertically oriented beddings and two with horizontal beddings.

After obtaining the cores, they were saturated using 2.5% KCl solution for 24 hours. Saturation was done to enhance the sensitivity and improve the quality of the NMR signal. By selectively saturating a particular nuclear spin state, the population distribution of the spins is modified, resulting in an increased population difference between the spin states of interest. This increased population difference leads to a larger NMR signal, thereby enhancing the sensitivity of the measurement. The choice of KCl solution was to ensure that the measurements reflect the natural state of the rock as closely as possible because it is chemically stable.

Similarly, cores (8 in total) were obtained from Chalk and Sandstone blocks. Eight of them were 1 inch in diameter with different lengths, as shown in Figures 2 and 5, whereas Figures 1, 3, and 4 show pictures of the Sandstone block and chalk from which the cores were extracted. After coring was completed, the samples were saturated using 2.5% KCl solution.

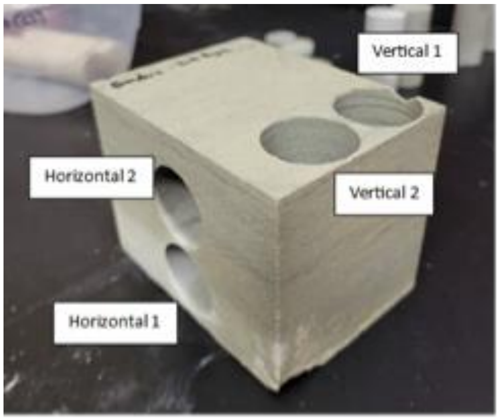


Figure 1: Bandera Sandstone block

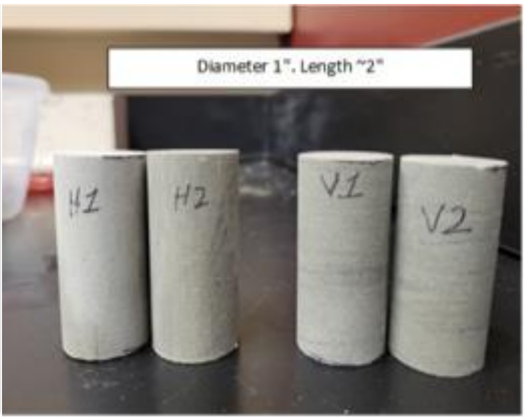


Figure 2: Bandera Sandstone cores

Figure 3: Chalk block

Figure 4: Berea Sandstone block

Figure 5: Chalk and Sandstone cores respectively

Table 1 below shows the dimensions of the cores utilized for this work.

Table 1: Summary of dimensions of utilized core samples

Sample name	Diameter (cm)	Length (cm)
Bandera sandstone (H1)	2.53	5.25
Bandera Sandstone (H2)	2.52	5.26
Bandera sandstone (V1)	2.53	5.11
Bandera sandstone (V2)	2.52	4.97
Chalk 1	2.53	5.08
Chalk 2	2.54	6.35
Berea Sandstone 1	2.53	8.20
Berea Sandstone 2	2.53	8.20

2.2 Sample preparation for artificial cuttings

The artificial cuttings were made using the following steps:

- Sandstone, Limestone, and Chalk rocks were crushed with a crusher and an industrial blender.
- The generated cuttings were sieved using different mesh sizes.
- After sieving, the cuttings were grouped into four different mesh sizes: 10, 18, 35, and <35.
- Cuttings were saturated for 24 hours in 2.5% KCl solution to enhance the sensitivity and improve the quality of the NMR signal.

After the samples were prepared, the next step was to carry out porosity measurements. The flowchart below summarizes the experimentation procedure utilized in this work.

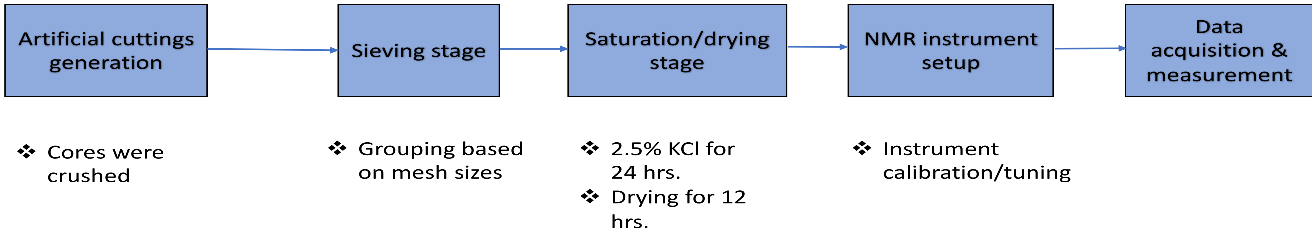


Figure 6: Flowchart summarizing experimental procedures

3. RESULTS

3.1 Bandera Sandstone Core

T_1 and T_2 relaxation measurements were acquired for all samples and were exported for data processing and analysis. Three T_1 and T_2 measurements were obtained for each saturated sample, making a total of 24 measurements and eight measurements were collected for the dry cores as shown in Table 2 below. The result showed that the T_1 and T_2 porosity were approximately the same as shown in the error column in Table 2 which indicates consistency of the results from the machine.

Table 2: Summary of NMR porosity for saturated and dry cores

Cores	H1	H2	V1	V2
1st Round (Saturated)				
T_2 Porosity (p.u)	7.9	11.9	10.6	9.6
T_1 Porosity (p.u)	8.4	10.9	10.2	9.9
2nd Round (Saturated)				
T_2 Porosity (p.u)	7.8	11.6	10.3	9.6
T_1 Porosity (p.u)	8.1	10.8	10.4	9.5
3rd Round (Saturated)				
T_2 Porosity (p.u)	7.9	11.7	10.5	9.8
T_1 Porosity (p.u)	7.4	10.7	9.8	8.6
Average	7.9	11.3	10.3	9.5
Standard Deviation	0.3	0.5	0.3	0.5
Dry Condition				
T_2 Porosity (p.u)	6.5	9.7	8.9	8.3
T_1 Porosity (p.u)	6.6	9.3	9.0	8.0

3.2 Bandera Sandstone artificial cuttings

T_1 and T_2 relaxation measurements were acquired for all samples and were exported for data processing and analysis. Three T_1 and T_2 measurements were obtained for each cutting size, and 48 measurements were taken, as shown in Table 2. The result also showed that the T_1 and T_2 porosity values aligned with each other.

Table 3: Summary of NMR porosity for saturated and dry cuttings

Artificial cuttings	Mesh 10	Mesh 18	Mesh 25	Mesh 35
1st Round (Saturated)				
T_2 Porosity (p.u)	7.1	24.2	27.6	24.9
T_1 Porosity (p.u)	7.4	22.4	28.5	22.9
2nd Round (Saturated)				
T_2 Porosity (p.u)	7.4	24.0	27.4	24.6
T_1 Porosity (p.u)	7.7	22.1	27.7	23.7
3rd Round (Saturated)				
T_2 Porosity (p.u)	7.9	23.9	27.3	24.7
T_1 Porosity (p.u)	6.7	23.5	28.9	22.7
Average	7.4	23.4	28	34
Standard Deviation	0.4	0.9	0.6	0.9
1st Round (Dry)				
T_2 Porosity (p.u)	5.3	22.4	25.6	21
T_1 Porosity (p.u)	4.9	21.4	24.9	19..5
2nd Round (Dry)				
T_2 Porosity (p.u)	5.5	22.7	25.7	20.5
T_1 Porosity (p.u)	5.6	22.0	24.8	19.4
3rd Round (Dry)				
T_2 Porosity (p.u)	5.5	22.4	25.2	20.6
T_1 Porosity (p.u)	6.4	21.8	24.4	18.9
Average	5.5	22	25	20
Standard Deviation	0.5	0.5	0.5	0.8

Furthermore, cutting samples-mesh 10 and 35 were utilized for a series of tests. This was done in an attempt to record previously obtained porosity values. The following steps were taken:

- The samples were measured (T_2) at an initial condition -completely dry (approximately 2 weeks).

- The samples in the vial were then filled with KCl solution and left to saturate for 15 minutes, after which the porosity was measured and recorded.
- Next, the excess solution was drained out of the samples, and the porosity was measured and recorded.
- The porosity values were then measured at 24hrs, 48hrs, and 72hrs air-dried conditions.

Table 4: NMR porosity for mesh 10

Condition	NMR porosity (p.u)	NMR porosity (p.u)
Initial dry (2 weeks)	4.3	4.1
Soaked	31.7	31.3
No excess Solution	17.4	17.4
24 hrs. dry	17.6	17.6
48 hrs. dry	15.2	15.3
72 hrs. dry	14.5	14.4

Table 5: NMR porosity for mesh 35

Condition	NMR porosity (p.u)	NMR porosity (p.u)
Initial dry (2 weeks)	18.3	17.7
Soaked	63.8	62.2
No excess Solution	47.6	46.6
24 hrs. dry	40.9	40.1
48 hrs. dry	33.0	33.1
72 hrs. dry	28.4	28.3

The same testing procedures were repeated, but this time with only mesh 10 cuttings and similar trend was observed of decreasing porosity as drying time was increased (Table 6).

Table 6: Repeated NMR porosity for mesh 10

Condition	NMR porosity (p.u)	NMR porosity (p.u)
Initial dry (2 weeks)	13.3	12.7
Soaked	30.6	30.3
No excess Solution	17.7	17.5
72 hrs. dry	14.5	14.0
96 hrs. dry	12.6	12.8

3.4 Chalk Sample

T_1 and T_2 porosity measurements were acquired for the Chalk Samples. The results are given in Table 7.

Table 7: NMR porosity of Chalk cores

Sample	T_1	T_1	T_2	T_2
Chalk 1	10.16	10.16	9.65	9.70
Chalk 2	12.74	12.4	12.19	12.17

T_1 and T_2 porosity measurements were acquired for the Chalk cuttings. The results for saturated and air dried cuttings are given in Table 8 and 9 respectively.

Table 8: NMR porosity of saturated chalk cuttings

Mesh size	T_1	T_1	T_2	T_2
Mesh 35	45.58	44.07	42.23	41.24
Mesh 25	30.51	31.23	29.83	29.80
Mesh 18	21.44	22.01	21.71	22.08
Mesh 10	14.95	14.63	13.83	13.96

Table 9: NMR porosity of air dried cuttings

Mesh size	T_1	T_1	T_2	T_2
Mesh 35	39.37	40.32	37.62	36.89
Mesh 25	28.97	27.95	27.72	27.71
Mesh 18	19.42	19.17	20.03	20.13
Mesh 10	13.71	13.09	13.09	13.35

3.5 Berea Sandstone Sample

The table below shows the results obtained for cores and cuttings of Berea Sandstone.

Table 10: NMR Porosity of Berea Sandstone cores

Sample	T_1	T_1	T_2	T_2
Sand 1	9.69	10.02	9.07	9.21
Sand 2	9.01	8.77	8.69	8.15

Table 11: NMR Porosity of Berea Sandstone cuttings

Mesh size	T_1	T_1
Mesh 35	33.68	33.51
Mesh 25	26.85	26.96
Mesh 18	20.05	21.00
Mesh 10	10.89	10.80

4. DISCUSSION

The work highlights the crucial role of real-time prediction of subsurface formation properties during the drilling process, emphasizing its significance in high-performance drilling activities, particularly in the context of geothermal wells. The key proposition is the integration of machine learning and AI in predicting formation properties, leveraging real-time measurements to enhance accuracy and reduce reliance on physical experiments.

The use of NMR with cuttings is presented as a cost-effective and time-efficient alternative to traditional core analysis methods, which can be both costly and time-consuming. The experiment conducted in the paper focused on porosity measurements of artificially generated cuttings from sandstone and limestone blocks, ranging from 0.5 to 2mm. The results reveal an interesting trend where, as the cutting size increases, the porosity value becomes closer to that of the core. This trend is more pronounced in the case of sandstone samples. Additionally, the study explores various conditions, including saturation levels and drying times, and establishes an inverse relationship between porosity and drying time.

The implications of these findings are valuable for the energy industry, as they suggest that NMR technology with drill cuttings can revolutionize how essential data for reservoir management is gathered. By harnessing the trends observed and developing predictive models that consider factors such as cutting size and drying time, it becomes possible to rapidly assess porosity in real-time. This not only offers a more cost-effective and time-efficient approach but also has the potential to provide more accurate insights for informed decision-making in the energy sector.

Figure 7-18 represents the NMR porosity in the context of T_2 relaxation times and from the plots, it can be established that the smaller the cuttings size, the higher the porosity value. As seen below, mesh 25 and 35 exhibited noisier NMR profiles and recorded the highest porosity value across all samples. This trend can be attributed to presence of interstitial water introducing noise and having a major impact on the reliability of the measurements and is linked to the variations observed in the NMR porosity values. The pronounced peaks in the T_2 relaxation times, particularly for mesh 25 and 35, indicate higher porosity, suggesting that the interstitial water content in these samples plays a significant role in the measurement. It is important to note that the presence of interstitial water can influence NMR measurements, introducing complexities that may affect the reliability of the results. Additionally, the impact of noise in the measurements cannot be overlooked, as it may contribute to variations in the observed porosity values.

Understanding the relationship between T_2 relaxation times and porosity is crucial for interpreting the NMR data accurately. This information is valuable for reservoir characterization, as porosity is a key parameter in assessing the storage and flow of fluids within rock formations. Furthermore, the influence of interstitial water and noise underscores the need for careful consideration and calibration in NMR measurements. This work explored different conditions, including excess solution, no excess solution, and varying drying times, contributes to a comprehensive understanding of the factors affecting NMR porosity measurements.

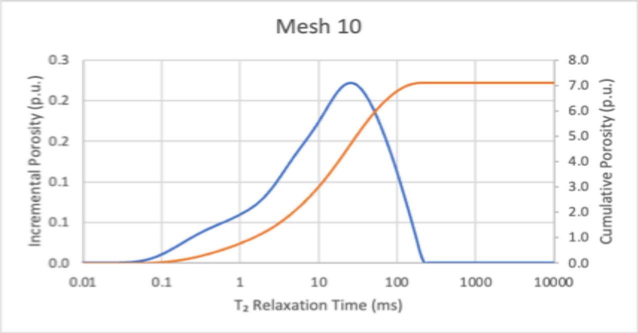


Figure 7: T_2 relaxation time for mesh 10 Bandera cuttings

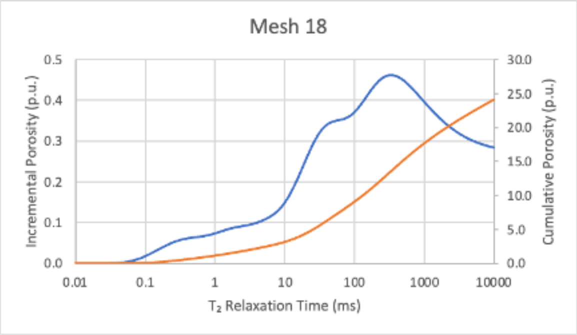


Figure 8: T_2 relaxation time for mesh 18 Bandera cuttings

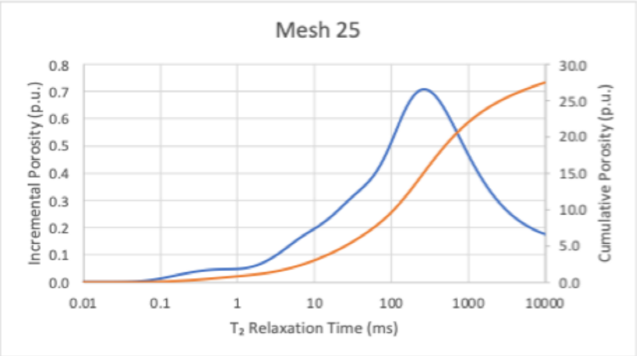


Figure 9: T_2 relaxation time for mesh 25 Bandera cuttings

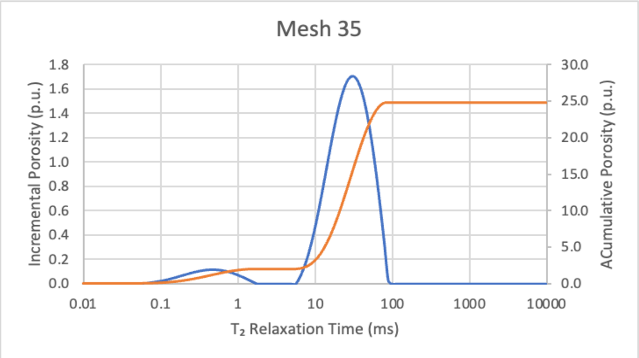
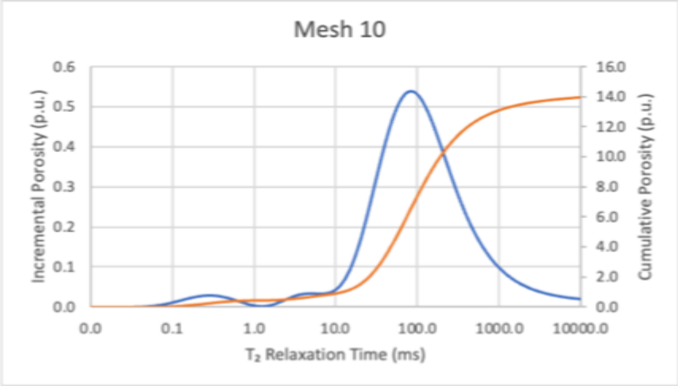


Figure 10: T_2 relaxation time for mesh 35 Bandera cuttings



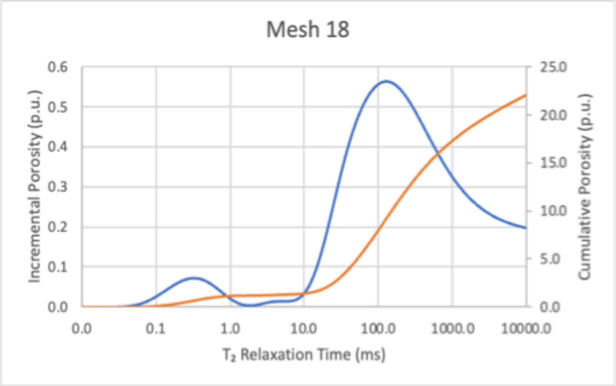
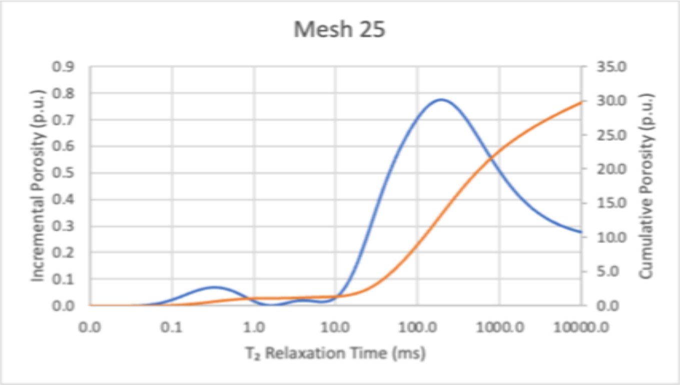


Figure 11: T_2 relaxation time for mesh 10 Chalk cuttings

Figure 12: T_2 relaxation time for mesh 18 Chalk cuttings



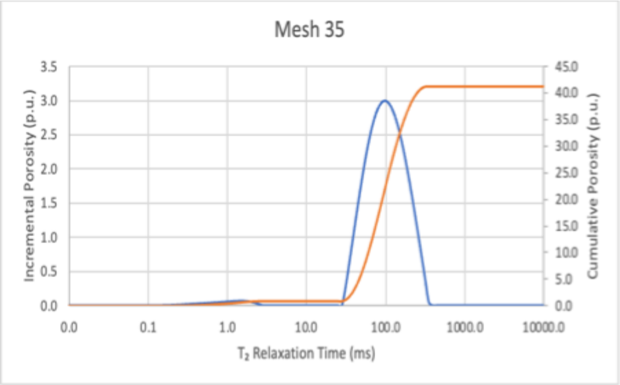
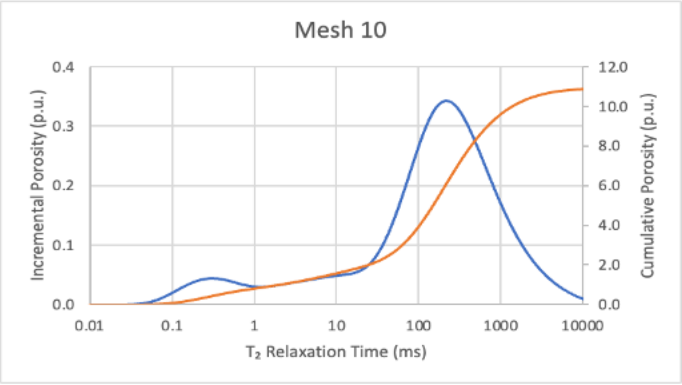


Figure 13: T_2 relaxation time for mesh 25 Chalk cuttings

Figure 14: T_2 relaxation time for mesh 35 Chalk cuttings



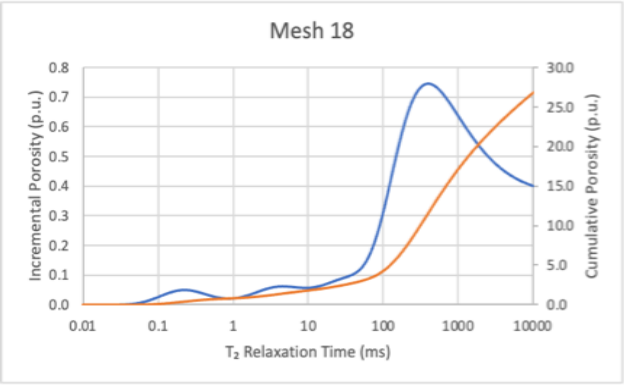


Figure 15: T_2 relaxation time for mesh 10 Berea cuttings

Figure 16: T_2 relaxation time for mesh 18 Berea cuttings

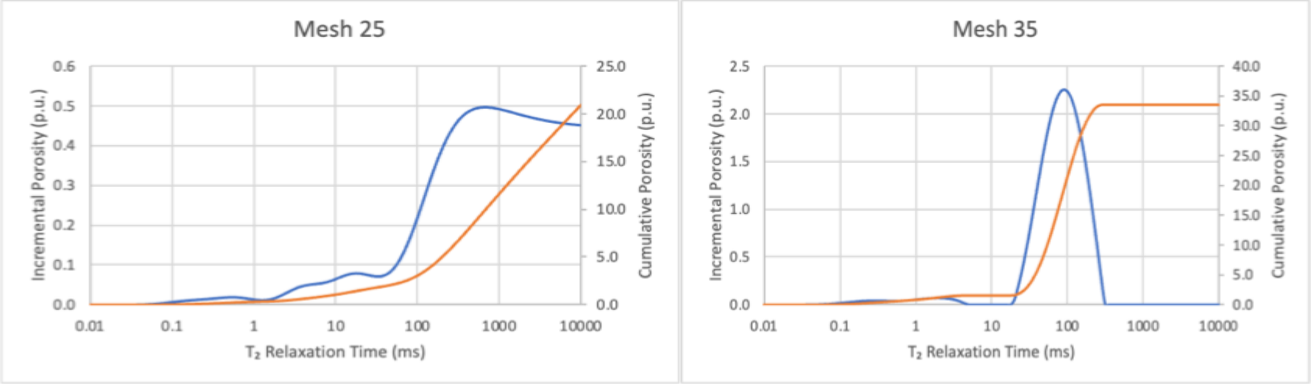


Figure 17: T_2 relaxation time for mesh 25 Berea cuttings

Figure 18: T_2 relaxation time for mesh 35 Berea cuttings

A comparison between the porosity values obtained for cuttings and cores reveals that the results are a close match. Figure 19 shows that the values were within 25% of each other across all samples. This enforces the idea that cuttings are representative of core samples and can be useful in studying and obtaining formation porosity.

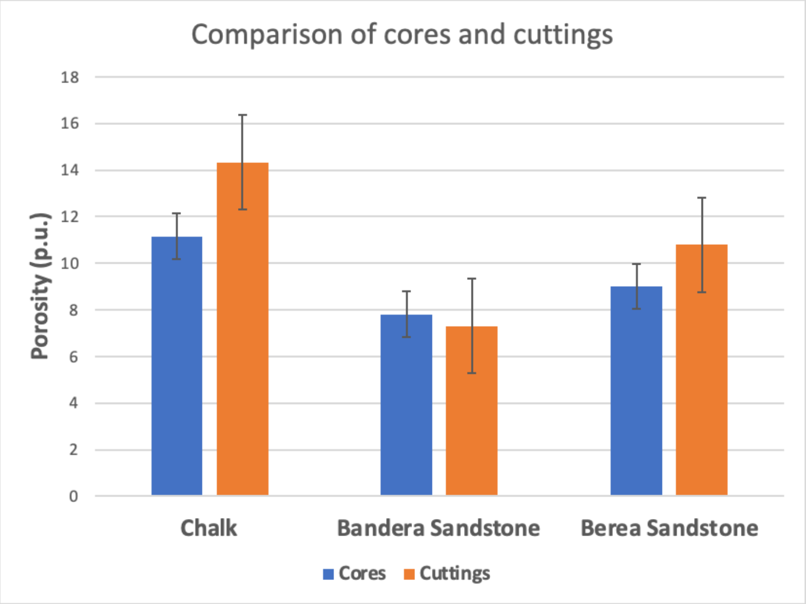


Figure 19: Comparison of cores and cuttings across all samples

4. CONCLUSIONS

The purpose of this study was to determine whether porosity could be reliably measured using NMR technology on drill cuttings and to develop testing protocols that would replicate field conditions and yield relevant data for potential machine learning applications.

Based on the work done, it can be concluded that drill cuttings are a good source for learning and understanding reservoir properties and are a cost-effective option for studying formation parameters and obtaining subsurface data. Apart from being readily available for all drilled wells, they can provide information about the reservoir throughout all phases of field development. Despite the limitations associated with using cuttings for NMR measurements, several authors and researchers have devised ways of optimally utilizing cuttings for measurements. However, due to surface water effects and representativeness issues, caution must be taken when using cuttings to estimate porosity.

The size of cuttings plays a huge role and has an impact on the desired result. Most recommended diameters from the literature are between 2 to 3mm. Preprocessing the cuttings before analysis is the most crucial step. Cuttings used for the testing must be sorted according to the size. Removal of interstitial water is also an important step, as it impacts T_2 relaxation values.

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