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T_1-T_2 NMR on Shale Cuttings

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Abstract

In recent years, nuclear magnetic resonance (NMR) core applications have expanded rapidly due to the prolific increase in horizontal drilling. One new application is NMR porosity measurement on cuttings. Green Imaging Technologies (GIT) developed an NMR porosity measurement on PDC and non-PDC cuttings that measures within 5% of the porosities obtained from rock core plugs and logging data. The objective here is to extend this measurement with other techniques commonly found in NMR rock core analysis and NMR well logging. T_1-T_2 NMR in traditional measurements has been used for fluid typing and organic content characterization and in this work we have extended that methodology to cuttings. In general, measurements in horizontal wells are limited to only a gamma ray and cuttings. Few wireline logs or cores are taken during the development phase. Using cuttings NMR measurements allows for more frequent measurements for minimal cost to resolve such issues as well spacing or heterogeneous changes in unconventional resources in laterals. Using NMR measurements on cuttings to replace or supplement NMR core analysis and horizontal wireline logging would be extremely beneficial, technically and financially.

Inversion recovery-CPMG (IR-CPMG) NMR pulse sequence is used to simultaneously measure T_1 and T_2 relaxation times on rock core plugs, crushed core plugs to PDC bit size and PDC cuttings from similar depths. Data acquisition is done on a 20 MHz NMR spectrometer. The data is then displayed on a 2D map, with T_2 on x-axis and T_1 on y-axis. The T_1-T_2 map can be divided into regions and based on how much NMR signal is present in each region, the distinct hydrocarbon species can be deduced. In samples from unconventional oil and gas wells the regions correspond to bitumen, clay bound water, free water and free hydrocarbon content. Samples were studied in as received, dry, 100 % Sw, 100% So and mixed saturated sample states in order to test the robustness of the T_1-T_2 map method. Cuttings sample preparation closely followed the steps from our previous URTeC and SCA publications on NMR based porosity measurement

on cuttings. Comparison of NMR data was done on datasets from rock core plugs, crushed plugs, NMR well log and original well cuttings.

Utica, Marcellus, Madison and Woodford samples were measured. The results from cuttings were within 5% of routine helium porosities on corresponding plugs. In some cases wettability and rock type played a factor in determination of porosity and permeability. Limitations from the acquisition can largely be removed by some a-priori information on the cuttings to help with sample preparation and more accurate cuttings' depth information. In summary, the developed methodology on PDC bit cuttings works not only on a singular rock type but is transferable among different rock types and maturities. It appears to be a cheap and accurate method to determine key volumetric components for operators in unconventional resources. Lastly the ability to take multiple samples along the lateral could help future determination of heterogeneity which is a possible culprit for varied EUR response in specific plays. The results of this study are very encouraging and imply the measurement could become routine in labs and well sites especially when logging or coring is impractical.

Introduction

Nuclear Magnetic Resonance (NMR) is widely used in the oil and gas sector to investigate both the types of fluids present and the porosity of the oil bearing rocks (Coates et al). In recent years, we have expanded the suite of NMR oil and gas measurements by developing a new method for determining the porosity of drill cuttings (Dick et al., Ganser et al., Dick et al.). In our previous work, we have validated our measurement by showing that the porosity derived for cuttings is consistent with the porosity of core samples taken at similar depths from the same well.

Our porosity of cuttings measurement employs T_2 distributions and as we have shown previously the T_2 distribution measured from cuttings is consistent with that measured for core plug taken at similar depth in the same well. This is an advantage of our technique for measuring the porosity of cuttings. Pore size distributions can be vital for determining not just the porosity of samples but also size of the pores within a sample. This pore size information can lead to informed decisions about how difficult retrieving oil from the well of interest will be. No other measurement of the porosity of cuttings offers this information in addition to porosity.

The objective of the work presented in this paper is to extend our porosity of cuttings measurement to include other techniques commonly found in NMR rock core analysis and NMR well logging. Specifically, we are interested in retrieving T_1-T_2 maps for cuttings. These maps can be used for fluid typing and organic content characterization. This would make T_1-T_2 maps of cuttings an indispensable tool in the characterization of wells.

Theory and/or Methods

To derive porosity, the pore volume and the bulk volume of a sample are required. For core plug analysis, measuring the bulk volume is simple as it can be determined by measuring its length and diameter. Measuring the porosity of cuttings is not so straightforward as measuring their geometry is impossible. To circumvent this issue, we determine the porosity of cuttings according to Equation 1.

$$Porosity = \frac{Pore\ Volume\ Of\ Cuttings}{Bulk\ Volume\ Of\ Cuttings} = \frac{V_{Pore}}{V_{Total} - V_{Pore+Fluid} + V_{Pore}}$$

Three independent measurements that are straightforward to achieve using NMR are completed. As described in the right panel of Figure 1, V_{Total} is the total volume of a glass tube, V_{Pore} is the pore volume of the cuttings sample and $V_{Pore+Fluid}$ is the volume of fluid in a glass tube partially filled with brine and saturated cuttings.

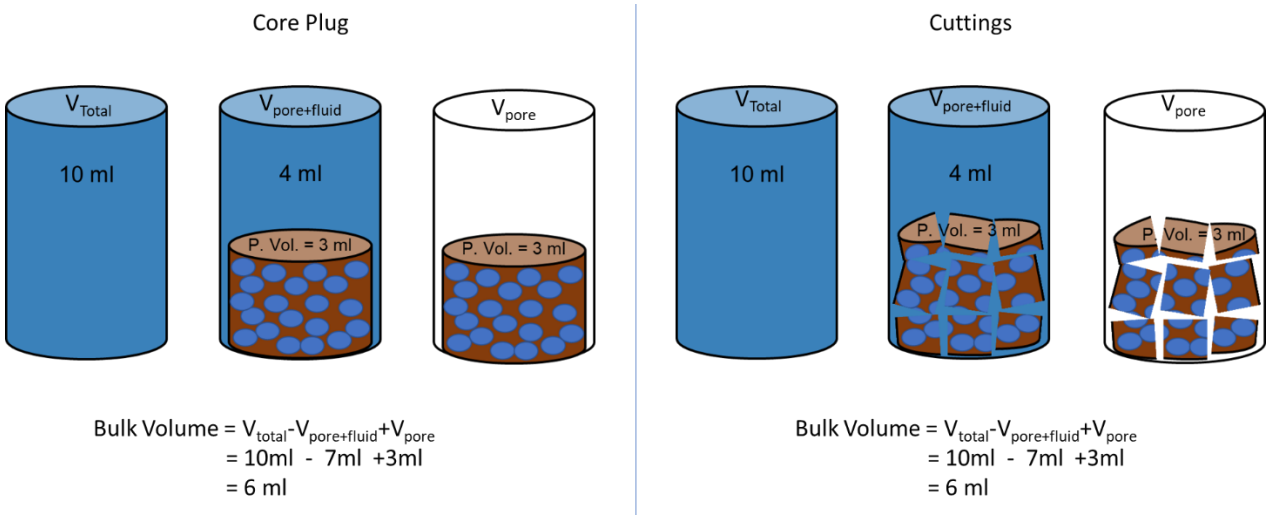

Figure 1: To retrieve the bulk volume of the cuttings, three measurements are made. V_{Total} is the total volume of a glass tube, V_{Pore} is the pore volume of the cuttings sample and $V_{Pore+Fluid}$ is the volume of fluid in a glass tube partially filled with brine and saturated cuttings. The left panel shows how three measurements are combined to yield bulk volume for core sample as well as crushed sample or cuttings.

Figure 1 also illustrates how these three measurements can be combined to yield the bulk volume of the cuttings. It is easiest to understand if you first consider a core plug in lieu of cuttings (Figure 1 – left panel). First the volume of a glass tube filled with brine is measured (V_{Total} = 10 ml). Next a fully saturated core sample is placed into the tube, the brine is displaced and the observed volume is measured ($V_{Pore+Fluid}$ = 7 ml). In the example illustrated in Figure 1, this corresponds to 3 ml of NMR signal for the volume within the pores of the sample along with 4 ml of signal for the fluid surrounding the core. Finally, the plug is removed from the vial and its pore volume alone is measured (V_{Pore} = 3 ml). Then applying the equation for bulk volume, the bulk volume of the core plug is determined to be 6 ml. This procedure is similar to how the bulk volume of an irregular shaped object can be determined by submerging it in water and observing how much volume is displaced. Obviously, it would make no sense to measure the bulk volume of a core plug with this method. However as shown in the right panel of Figure 1, the same procedure can be applied to cuttings whose bulk volume cannot be easily measured by other methods.

In principle, employing this method for determining the porosity of cuttings is straightforward. However, in practice application of the method is not so easy. Between the measurement of $V_{Pore+Fluid}$ and V_{Pore} any fluid on the surface of the cuttings needs to be removed. As shown in Figure 2, if it is not removed signal from this surface fluid can be included in the measurement of V_{Pore} leading to an overestimate of the cuttings porosity as well as an inaccurate T_2 distribution for the cuttings. In addition, the problem is accentuated for the smaller cuttings where the surface to volume ratio is large. This is not an issue for core plugs because their surface to volume ratio is smaller.

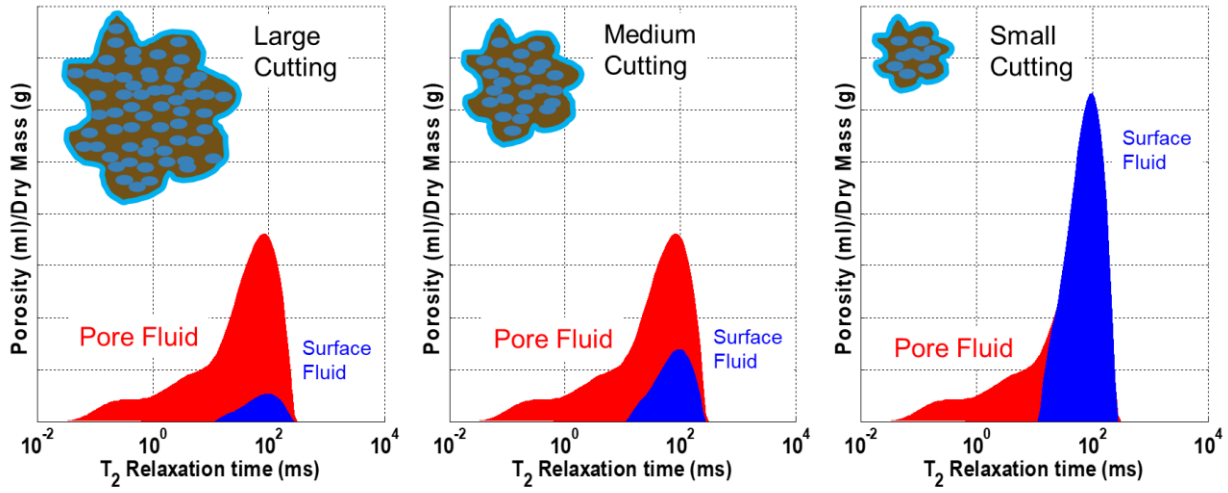

Figure 2: Removal of fluid from the surface of the cuttings is key to accurate determination of porosity. NMR signal from fluid on the surface of cuttings can overlap with signal from fluid within the pores of the cuttings. This can lead to an overestimate of the porosity. Surface fluid is more of an issue for smaller cuttings because of their larger surface to volume ratios.

As outlined in our previous work (Dick et al., Ganser et al., Dick et al.), a large effort has gone into how to best remove the fluid from the surface of the cuttings without disturbing the fluid within the pores of the sample. It was determined that employing a combination of rinsing the cuttings with D_2O and centrifuging them is the most effective method for eliminating the fluid from the surface of the cuttings. D_2O is NMR invisible, so essentially during the rinsing process the NMR visible fluid on the surface of the cuttings is replaced by D_2O (Dick et al.). We have outlined our procedure for removing fluid from the surface of cuttings in detail previously, so only a brief summary of the procedure we employed in this study will be presented here.

1) Fill a Teflon vial with 2% KCl brine and measure its volume (V_{Total}). This vial was specifically designed for this porosity of cuttings measurement.

2) Weigh three grams of cuttings and vacuum saturate them with 2% KCl brine in the vial.

3) Measure the volume of fluid in the vial which is now partially filled with brine and saturated cuttings ($V_{Pore+Fluid}$).

4) Rinse the cuttings sample in the vial with D_2O via centrifugation.

5) Measure the pore volume of the cuttings (V_{Pore}). The T_1-T_2 maps were also measured at this stage.

All the volume measurements were completed using a CPMG NMR pulse sequence (Meiboom et al.). For the V_{Pore} measurement, this sequence yields the pore size distribution. The parameters for each sequence can be found in Table 1. For the T_1-T_2 maps, a inversion recovery-CPMG (IR-CPMG) NMR pulse sequence (Song et al.) is used to simultaneously measure T_1 and T_2 relaxation times. All data was recorded on an Oxford-Instruments MQC$^+$ NMR spectrometer from Oxford Instruments operating at 20 MHz. Green Imaging Technologies software was employed for data acquisition and analysis.

Table 1 – NMR Parameters.

Measurement	Pulse Sequence	Recycle delay (ms)	Signal to Noise Ratio	Tau (µs)	Number of Echoes
V_{Total}, $V_{Pore+Fluid}$	CPMG	750	100	100	100000
V_{Pore}	CPMG	750	100	100	2500

Measurement	Pulse Sequence	Recycle Delay (ms)	Signal to Noise Ratio	Tau (us)	Number of Echoes	Number of T1 steps
T1-T2	IR-CPMG	750	100	100	2500	30

The cutting samples came from one well located in the Woodford formation. A 4" whole core was taken on the same well. The core was sampled at a density of 5 ft spacing. Porosity, grain density, bulk density and saturation were determined using conventional routine core analysis methods and the saturations and porosities were measured using both retort and Dean-Stark methodology. Plugs from the same well at similar depths as the cuttings were provided for verification of the results. The porosity, pore size distributions and T_1-T_2 maps for the plugs were probed using the same NMR parameters as those employed for the cuttings (Table 1). In addition, a few of the plugs were crushed to create crushed core (or pseudo cutting) samples. These samples can then be run through the procedure for determining the porosity of cuttings. This offers further verification of the cuttings porosity measurements. So to sum up, three porosity data sets were compared in this study. The samples used were from intact plugs, crushed plugs to form pseudo-cuttings and finally the actual PDC drill bit cuttings that came up the mud system from the approximate depth of the plugs.

Results

Table 2 summarizes the porosity derived in this study for the core plug, crushed core plug and cutting samples. The cuttings were sampled in windows of five feet of depth for example 9520 to 9525 ft. Plugs were chosen so that there was at least one plug within each cutting sample window. In addition, crushed plug samples were created from plugs 1H, 2Ha, 4H and 5H. In general, the porosity of the cuttings, plugs and crushed samples all show that the porosity of this well is quite low (1-4 p.u.).

Table 2 – Porosity Results.

Plug	Plug Depth (ft)	Previous Retort Porosity (p.u.)	Previous Dean Stark Porosity (p.u.)	Plug Porosity (p.u.)	Crushed Plug Porosity (p.u.)	Cutting Depth (ft)	Cutting Porosity (p.u.)
1H	9525.7	2.68	5.54	0.56	0.94	9520	1.93
						9525	2.35
						9530	1.41
2Ha	9539.2	2.73	4.32	0.9	1.62	9545	0.81

2Hb	9539	2.73	4.32	1.2	N/A		
3Ha	9556.4	3.1	4.34	1.6	N/A	9550	1.27
3Hb	9556.95	3.1	4.34	2	N/A	9560	1.93
4H	9571.15	5.04	8.182	1.1	3.4	9565	1.5
						9570	2.28
						9575	1.33
5H	9592.2	3.16	5.45	4	1.3	9585	1.12
						9590	2.55
						9595	1.18

The accuracy of the cuttings porosity measurement is on the order of one p.u. so the results summarized in Table 2 were pushing the limits of our measurement capabilities. The low porosity lead to a low signal to noise ratio for the NMR measurements. This meant it is more difficult to assess the agreement between the porosity derived from the core plugs with that derived from the crushed core or cutting samples. However, in general it appears that the porosity derived from the cuttings is slightly higher than that derived for the plugs. Any disagreement between the porosity of the plugs and that of the cuttings is typically attributed to the fact that the porosity derived from the plugs is a point measurement while the porosity derived from the cuttings is an average over the window of depth at which the cuttings were retrieved.

Another way to confirm the porosity derived for the samples investigated in this work is to compare them with previous results. The low porosity is consistent with previous retort measurements but was does not match the Dean-Stark data. The new measurements are consistently lower than the Dean-Stark'd plugs. There is some suspicion that the Dean-Stark method may have dissolved some soluable solid hydrocarbon, aka bitumen. However, pre and post solvent extracted LECO results showed minimal bitumen content. Overall, all the current round of plug porosities and the cutting data showed porosities that were 70-50% of the previous routine core work. Another consideration is that halite or other evaporites related to formation water may have precipitated in the samples due to high oilfield brine salinities. The solvents used in the Dean-Stark process may have dissolved these salts but they may have been present when the NMR was performed. This assumes the 2% KCl used to re-saturate the samples was unable to dissolve the precipitates. This also illustrates the importance of the sample preparation.

Discussion

Beyond comparing porosity only, what makes our measurement unique is that the pore size distributions of core plugs, crushed plug and cutting samples can also be compared. This comparison offers an extra level of analysis that can lead to an understanding of the relative size of the pores within the sample. In addition, the pore size distributions may give insight as to why there are discrepancies between the porosity derived from the core, crushed and cutting samples. Figure 3 compares the pore size distribution for plug 1H

(Figure 3 – black trace) with the distribution for crushed core sample from plug 1H (Figure 3 – green trace) as well as the distributions for cuttings at depths of 9520 (Figure 3 – red trace), 9525 (Figure 3 – blue trace) and 9530 (Figure 3 – gray trace) feet. To normalize all the distributions on the same scale, the magnitude of the distributions is divided by the dry mass of the samples. The shape of each distribution is similar with each showing peaks in porosity between T_2 relaxation times of 0.1-10 ms. Figure 4 shows the pore size distributions for plugs 3Ha (Figure 4 – black trace) and 3Hb (Figure 4 – brown trace) compared with the pore size distributions for cuttings at depths of 9550 (Figure 4 – blue trace) and 9560 (Figure 4 – red trace) feet. Here there is excellent agreement between the pore size distributions of the plugs and the cuttings. As a result, these samples also had the best agreement in porosity between the plug and cuttings.

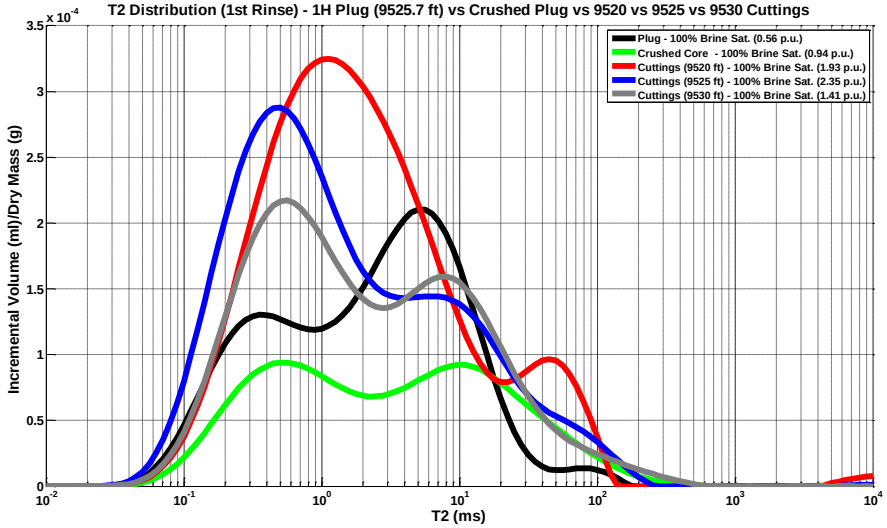

Figure 3: The pore size distribution for plug 1H (black trace) is compared with the distribution for the crushed core sample from plug 1H (green trace) as well as the distributions for cuttings at depths of 9520 (red trace), 9525 (blue trace) and 9530 (gray trace) feet. To normalize all the distributions on the same scale, the magnitude of the distributions is divided by the dry mass of the samples. The shape of each distribution is similar with each showing peaks in porosity between T_2 relaxation times of 0.1-10 ms.

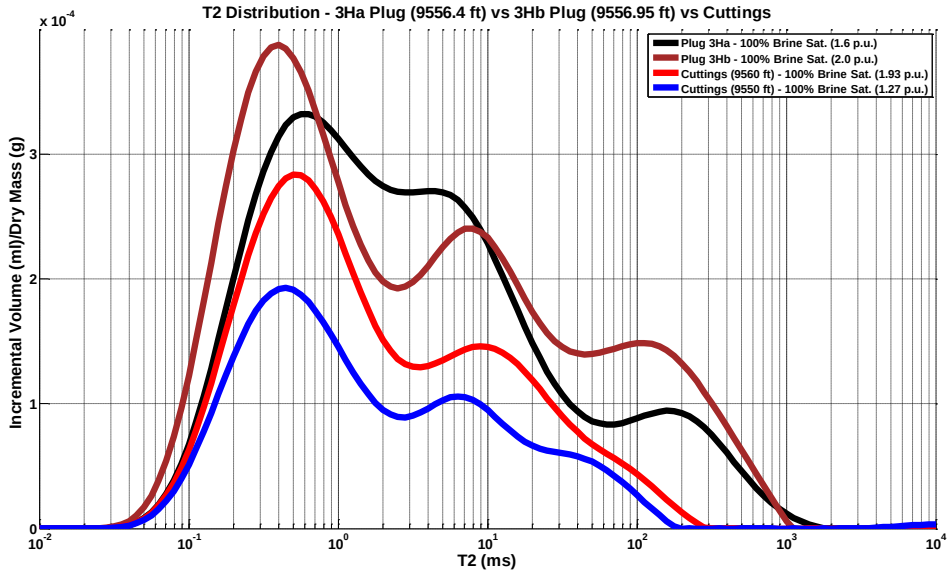

Figure 4: The pore size distribution for plugs 3Ha (black trace) and 3Hb (brown trace) are compared with the distributions for cuttings at depths of 9560 (red trace) and 9550 (blue trace) feet. To normalize all the distributions on the same scale, the magnitude of the distributions is divided by the dry mass of the samples. The shape of each distribution is similar.

The main purpose of this work was to explore expanding our cuttings measurement beyond porosity and pore size distribution measurements to T_1-T_2 maps. As mentioned earlier, T_1-T_2 maps are important for fluid typing in core samples. This is because a fluids location on a T_1-T_2 map is dependent on its viscosity. For example, heavy organic fluids such as bitumen will appear in the upper left quadrant of a T_1-T_2 map while clay bound water (CBW) and brine will appear in the lower left quadrant of a T_1-T_2 map. Finally, light hydrocarbons (HC) will appear in the upper right quadrant of a map. Figure 5 shows the T_1-T_2 map recorded for plug 1H. This sample contains mostly heavy organics and some free and/or clay bound water. This is consistent with the porosity determination which showed that the porosity of this sample was small approximately 1 p.u. The porosity determination of cuttings measurement does not include heavy organics in its calculation of porosity. The T_1-T_2 map is offering information beyond what the porosity determination measurement provided.

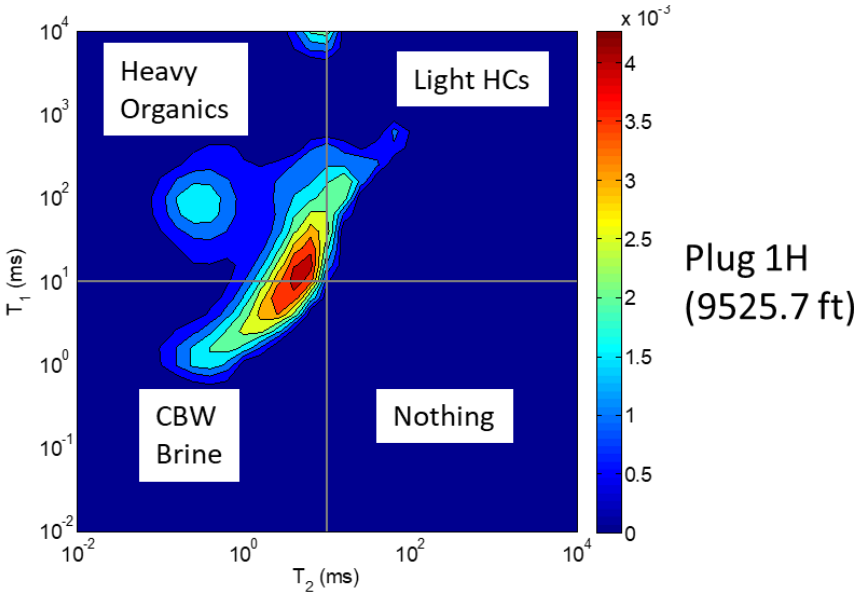

Figure 5: T_1-T_2 map for plug 1H. The map is broken into four quadrants. NMR characteristics separate different fluids into the quadrants based on their relative viscosities. The upper left quadrant contains signal from heavy organic molecules. The upper right quadrant contains signal from light hydrocarbons. The lower left quadrant contains signal from clay bound and free water. The lower right quadrant has no signal. T_1-T_2 maps allow fluid typing to be done on samples.

The question this work set out to answer was not the importance of T_1-T_2 maps but rather can accurate T_1-T_2 maps be derived from cuttings. Figure 6 shows the T_1-T_2 map for plug 1H (9525.7 ft) along with the maps for cuttings at depths of 9520, 9525 and 9530 feet. The maps for cuttings are consistent with the map for the plug with each showing heavy organic content and less free brine and/or clay bound water.

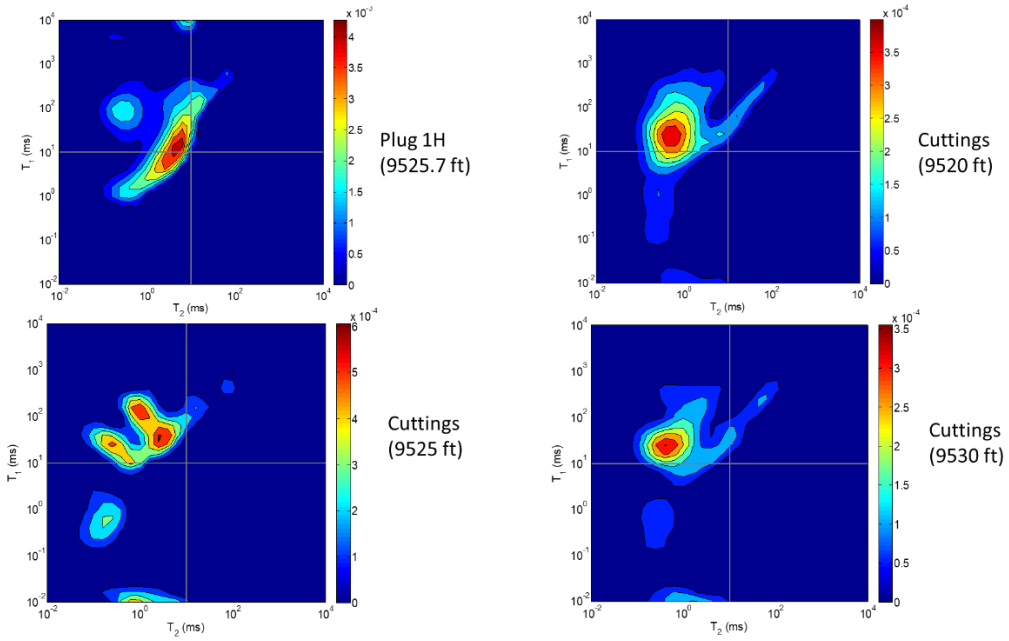

Figure 6: T_1-T_2 map for plug 1H (9525.7 ft) is shown along with the maps for cuttings at depths of 9520, 9525 and 9530 feet. The maps for cuttings are consistent with the map for the plug with each showing heavy organic content and less brine and/or clay bound water.

Figure 7 shows the T_1-T_2 maps for plug 3Hb (9556.95 ft) and cuttings at depth of 9560 ft. The maps are very similar with each showing content from heavy organics in the upper left quadrant. There is little clay bound water , water and light hydrocarbons in the plug or cuttings. This is consistent with the low porosity for determined for the cuttings and plug (1 – 2 p.u.).

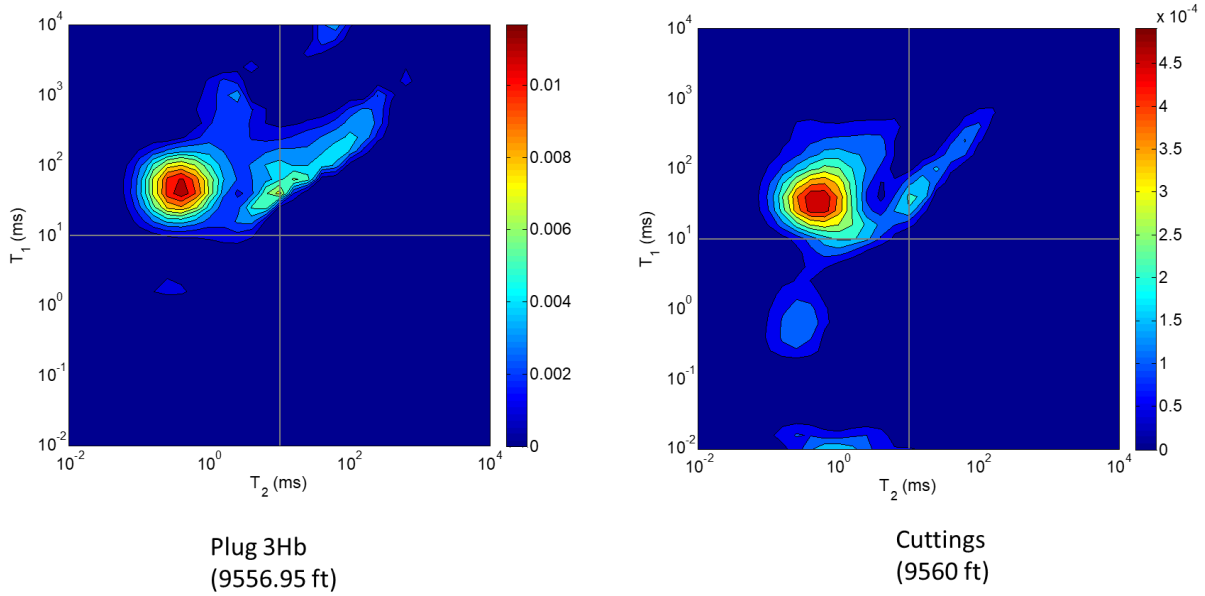

Figure 7: The T_1-T_2 maps for plug 3Hb (9556.95 ft) and cuttings at depth of 9560 ft are shown. The maps are very similar with each showing content from heavy organics in the upper left quadrant. There is little clay bound or free water or light hydrocarbons in the plug or cuttings. This is consistent with the low porosity for determined for the cuttings and plug (1 – 2 p.u.).

Conclusions

Employing our porosity of cuttings determination method, we have successfully determined the porosity for cuttings samples. To confirm the accuracy of our results, the porosity of cuttings was compared with the porosity determined for core plug and crushed plug samples taken from the same well. The cuttings and plug results were consistent with one another. Further, we compared the pore size distributions of several cuttings samples with their plug counterparts. The good agreement between the pore size distribution gave us further confidence in the validity of our measurement. This porosity determination and validation studies were repeat measurements of work done previously on different samples. Where this study differed from the previous work is that it pushed the cuttings measurement beyond porosity and pore size distributions to T_1-T_2 maps. Maps were successfully measured on various cuttings and were consistent with T_1-T_2 maps recorded for core plug samples from the same well at similar depths. The availability of T_1-T_2 maps, opens up a whole new suite of measurements that could be completed on cuttings samples. The results of this study are very encouraging and imply the measurement could become routine in labs and well sites especially when logging or coring is impractical. We plan on continuing this work on T_1-T_2 maps of cuttings by expanding it to include different wells of different geology.

References

Coates, G.R., Xiao, L., and Prammer, M.G., *NMR Logging. Principles & Applications*, Halliburton Energy Services, Houston, 1999.

Dick, M. J., Green, D., Kenney, T., Veselinovic, D., Tallarita, J., Smith, M.A., "Quick and Simple Porosity Measurement at the Well Site" Society of Core Analysts, Vienna, Austria, 28 August-1 September 2017.

Ganser, N., Wittman, B., Hemenway, M., Dick, M., Veselinovic, D., Kenney, T., Green, D. and Rowe, H., "Integration of Geochemical and Petrophysical Measurements from Drill Cuttings for Unconventional Reservoir Characterization, Converse County, Powder River Basin", Unconventional Resources Technology Conference, Houston, TX, USA, 20-22 July 2020.

Dick, M., "Accurate Measured Porosity On Cuttings Going Beyond T_2 Cutoffs" SPWLA The More You Know Webinar, June 2020.

Meiboom, S. and Gill, D., 1958. Modified Spin-Echo Method for Measuring Nuclear Relaxation Times, *Review of Scientific Instruments*, **29**, 688-691

Song, Y. Q., Venkataramanan, L., Hurlimann, M. D., Flaum, M., Frulla, P. and Straley, C., 2002. T_1–T_2 Correlation Spectra Obtained Using a Fast Two-Dimensional Laplace Inversion. *Journal of Magnetic Resonance*, **154**, 261-268

MQC+ User Manual, Version 1.X, Oxford Instruments.

GIT Systems and LithoMetrix User Manual, Revision 1.9, Green Imaging Technologies.