VALIDATION OF POROSITY OF NMR CUTTINGS

M.J. Dick, D. Veselinovic, T. Kenney and D. Green, Green Imaging Technologies

This paper was prepared for presentation at the SPWLA 63rd Annual Logging Symposium held in Stavanger, Norway, June 10-15, 2022.

ABSTRACT

Drill cuttings are ubiquitous in oil and gas well drilling operations, but beyond mud logging, cuttings are often discarded without analysis. Recently, there has been an up-tick in employing nuclear magnetic resonance (NMR) rock core analysis techniques to cuttings to unlock more information about oil and gas wells.

Deriving porosity of drill cuttings via NMR T_2-pore size distribution can be significantly influenced by surface fluid on the cuttings, acquired either during saturation of the cuttings in the lab or from cutting fluid at the well site, which can easily be misinterpreted as pore volume. Previous attempts to eliminate the surface fluid signal employed a cutoff to the pore size distribution curve to distinguish fluid in the pores (below the cutoff) from fluid on the surface (above the cutoff). Unfortunately, the use of cutoffs is prone to error as the position of the cutoff is difficult to determine accurately as signal from fluids in the pores can easily overlap with signal from fluids on the surface of the cuttings.

In recent years, we have developed a technique which eliminates signal from fluid on the surface of the cuttings removing the need to apply a cutoff. In this paper, we present a validation of this technique for determining porosity of cuttings based on NMR T_2 distribution measurements. A survey of hundreds of samples has been completed validating this technique for the porosity determination of cuttings. The paper will also include a discussion on the utility of the method on various rock types and reservoirs as well as an investigation of the advantages and limitations of the method. Specifically, the NMR porosity of cuttings measurement (applied to both polycrystalline diamond compact (PDC) and non-PDC cuttings) has shown porosities within 5% of the NMR porosities obtained from rock core plugs and logging data.

In addition to deriving the porosity, the T_2 distributions (related to pore size distributions) can unlock a whole new suite of parameters which can be derived from cuttings including the relative size of the pores and the bound vs. free fluid content in a well. Results will be shown that validate the T_2 distribution measured from cuttings in comparison with the T_2 distribution measured from core plugs. Most recently, work has focused on extending this NMR cuttings 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.

INTRODUCTION

Oil and gas wells are typically characterized (porosity, permeability, mineralogy, etc) via down hole logging tools and/or core analysis. These methods, when applied during drilling, either do not give immediate feedback or can be complex, expensive, or prone to error. Recently, there has been an increased interest in employing cuttings to unlock more information about the wells.

Nuclear Magnetic Resonance (NMR) has become more prevalent in the oil and gas sector over the past few decades (Coates et al., 1999). NMR core analysis is now routinely employed to investigate both the types of fluids present and the porosity of the oil bearing rocks. As the use of NMR has expanded so has the interest in applying NMR core analysis techniques to derive the porosity of cuttings. The two principal challenges to deriving the porosity of cutting samples via NMR is determining the bulk volume of the samples and removing fluid from the surface of the samples. In the last five years, several groups have made attempts to derive the porosity of cuttings samples via NMR (Dang et al., 2017, Althaus et al., 2019, Singer et al., 2021). These groups have handled the challenges inherent in determining the porosity of cuttings by employing different methods including applying a cutoff to the T_2 pore size distributions to distinguish surface fluid from pore fluid in the cutting samples and employing mass/density data to derive bulk volume. Further, Mitchell et al. (Mitchell et al., 2019) employed measurements at different magnetic field strengths with different fluids to distinguish surface fluid from pore fluid in the cuttings samples.

In recent years, we have developed a new method for determining the porosity of drill cuttings (Dick et al., 2017, Ganser et al., 2020, Dick et al., 2020, Dick et al., 2021). Our porosity of cuttings measurement employs T_2 distributions to determine both the pore volume and bulk volume of the samples. Our measurements are all done with a single saturating fluid at a single magnetic

field strength and do not employ additional data such as mass to derive bulk volume. This simplifies the porosity determination procedure and removes potential sources of error increasing the accuracy of the measurement. In addition, we remove the fluid from the surface of the cuttings by employing a combination rinsing the samples with D_2O and spinning them in a centrifuge. Removing the surface fluid ensures that fluid in the pores will not be confused with fluid on the surface of the cuttings during the T_2 distribution measurement. This ensures that the porosity is accurately determined from the T_2 data. In this paper, we will further explain the advantages of our porosity measurement technique along with presenting a survey of various samples which has been completed validating this technique for the porosity determination of cuttings.

METHODS

To derive porosity, the pore volume and the bulk volume of a sample are required. For core plug analysis, measuring the bulk volume of a cylindrical sample 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. Different groups have applied different procedures to determine bulk volume including using a combination of NMR volume measurements and mass measurements (Althaus et al., 2019) along with the density of the samples.

We employ a different procedure where three independent NMR measurements are employed to derive the porosity of the cuttings. As shown in Equation 1 and 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. All three of these measurements are in principle easy to determine via NMR. Employing only NMR data removes any uncertainty in the porosity measurement due to mass measurements or assumptions made in determining the density of the cuttings.

$$\text{Porosity} = \frac{\text{Pore Volume Of Cuttings}}{\text{Bulk Volume Of Cuttings}} = \frac{V_{Pore}}{V_{Total} - V_{Pore+Fluid} + V_{Pore}} \quad (1)$$

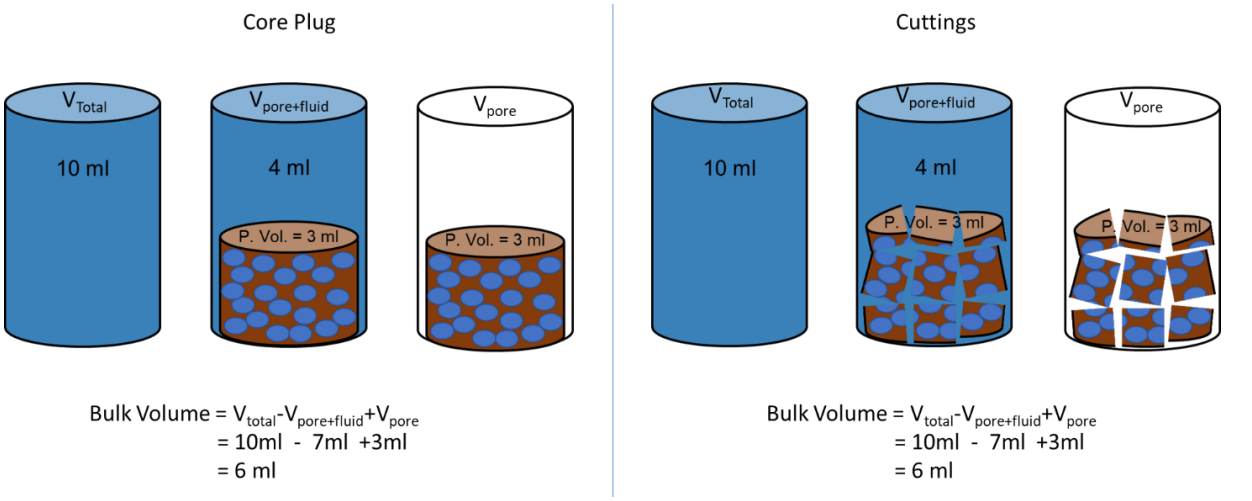

Fig. 1— To retrieve the bulk volume of the cuttings, three measurements are made. V_{Total} is the total volume of a glass tube, V_{Pore} is the pore volume of the cuttings sample and $V_{Pore+Fluid}$ is the volume of fluid in a glass tube partially filled with brine and saturated cuttings. The left 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 fluid around 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 the simulation 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. In their paper, Mitchell and coauthors (Mitchel et al., 2019) estimated the contribution of fluid on the surface of cuttings as function of size. For example, they determined that for a 1 mm diameter cutting with a surface fluid film of 10 µm, the measured porosity will be overestimated by approximately 6 p.u

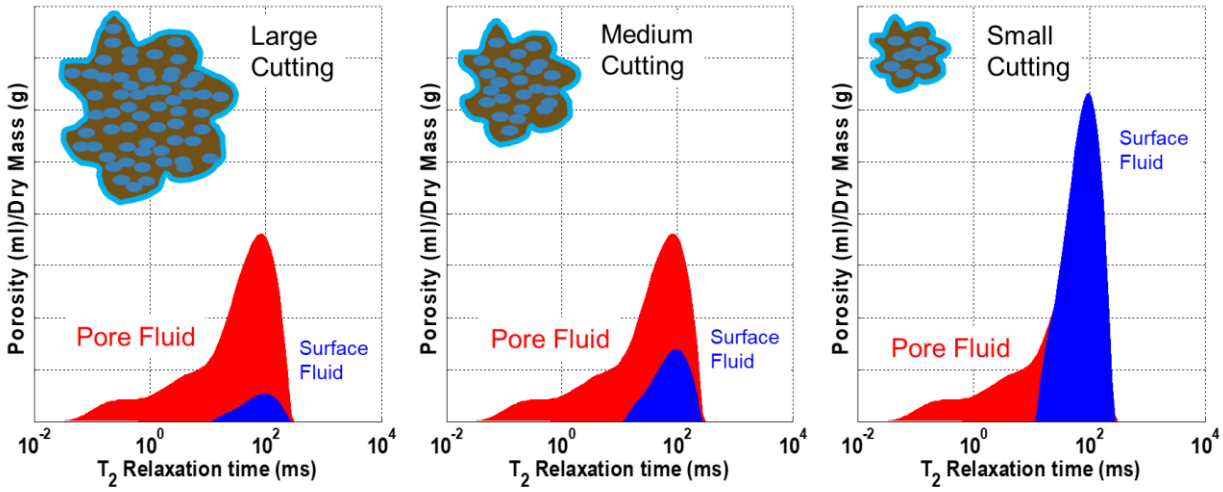

Fig. 2— Removal of fluid from the surface of the cuttings is key to accurate determination of porosity. NMR signal from fluid on the surface of cuttings can overlap with signal from fluid within the pores of the cuttings. This can lead to an overestimate of the porosity. Surface fluid is more of an issue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

One method which can be employed to remove signal from the fluid on the surface of the cuttings is to employ a cutoff to the T_2 distributions. In theory, the fluid on the surface of the cuttings would have a longer T_2 relaxation time than the fluid within the pores of the samples. However, in practice this is not the case with the signal from the surface of the cuttings often being overlapped with the signal from the fluid within the pores. Figure 3 shows an example of the T_2 distribution derived for a sandstone core plug (red trace) along with the distribution for bulk water (green trace). Also shown is the T_2 distribution for a crushed sample (blue trace) made from the same core plug. In this case, some of the surface fluid was removed from the crushed sample via paper towel drying. From the left-panel of Figure 3 it is clear that there is a significant contribution to the T_2 distribution of the crushed sample from the fluid on the surface. The peak at approximately 1500 ms can be attributed to surface fluid. If you were to disregard this surface fluid, blindly apply Equation 1 and derive the porosity of the crushed sample you would overestimate the porosity of the sample by almost a factor of three (core plug porosity – 10.5 p.u. vs. crushed sample porosity – 30.1 p.u.). The right-hand panel of Figure 3 shows how a cutoff could be applied to the T_2 data to derive a more accurate porosity for the crushed sample. If a cutoff is applied at 200 ms and all the signal above that point is attributed to fluid on the surface of the sample then a porosity of 7.1 p.u is derived. The problem with this cutoff method is that it is hard to know exactly where to apply the cutoff to optimally remove the signal from the surface of the cuttings without compromising the signal from within the pores of the sample. For the example shown in the right-hand panel Figure 3, the T_2 cutoff applied lead to an underestimate of the porosity by approximately 3 p.u

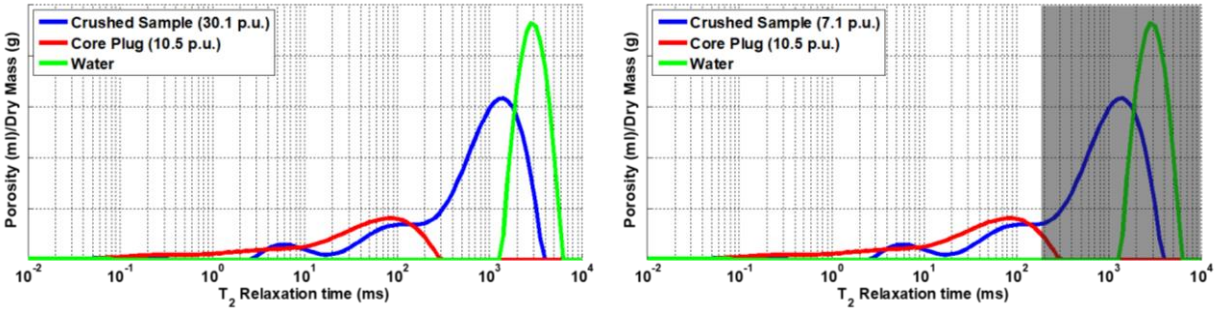

Fig. 3— T_2 distributions derived for a sandstone core plug (red trace) bulk water (green trace) and a crushed plug sample (blue trace) are shown. Some of the surface fluid was removed from the crushed sample via paper towel drying. In the left-panel, the peak at approximately T_2 = 1500 ms can be attributed to surface fluid. The right-hand panel of Figure 3 shows how a cutoff could be applied to the T_2 data to derive a more accurate porosity for the crushed sample. If a cutoff is applied at 200 ms and all the signal above that point is attributed to fluid on the surface of the sample then a porosity of 7.1 p.u is derived which still underestimates the known porosity of the sample by approximately 3 p.u.

The example shown in Figure 3 with crushed samples is a best-case scenario for application of a T_2 cutoff. In our experience, employing a T_2 cutoff to distinguish fluid on the surface of the cuttings from fluid within the pores of a sample gets even more difficult when applied to actual cuttings samples in lieu of crushed samples. Figure 4 shows a comparison of the T_2 distributions derived from a core plug (black trace) with that derived from cuttings (green trace). The cuttings and plug were taken from the same well at similar depths. Prior to acquisition of the T_2 data, an effort was made to remove as much water from the surface of the cuttings via spinning it off in a centrifuge. As can be seen from the left panel of Figure 4, there is a significant overlap between the T_2 distribution of the core plug and that of the cuttings. This overlap makes it impossible to distinguish fluid on the surface of the cuttings from fluid within the pores of the samples. In addition, if you were to apply no T_2 cutoff and derive the porosity of the cuttings employing the total volume observed for the cuttings via Equation 1 a porosity of 24.1 p.u. would be determined. This porosity is more than double the expected porosity derived from the plug data (11.2 p.u.).

The middle panel of Figure 4 shows the results for a possible T_2 cutoff analysis for the data shown. With no prior information about porosity or previous plug measurements, one might apply a T_2 cutoff near 50 ms thinking that the small peak around 110 ms originates from fluid on the surface of the cuttings. However, after application of this T_2 cutoff, a porosity of 21.5 p.u. is derived which is still nearly double the porosity expected from the plug data. This indicates that this T_2 cutoff has not done an effective job at eliminating the signal from fluid on the surface of the cuttings. Finally, the right-hand panel of Figure 4 shows where the T_2 cutoff would have to be applied to derive a porosity similar to that expected from the plug data. Clearly, applying the T_2 cutoff in this location makes no physical sense as it eliminates a significant portion of the signal within the pores of the sample. The right-hand panel clearly illustrates that with this data set it is impossible to distinguish signal from fluid on the surface of the cuttings from fluid within the pores of the cuttings.

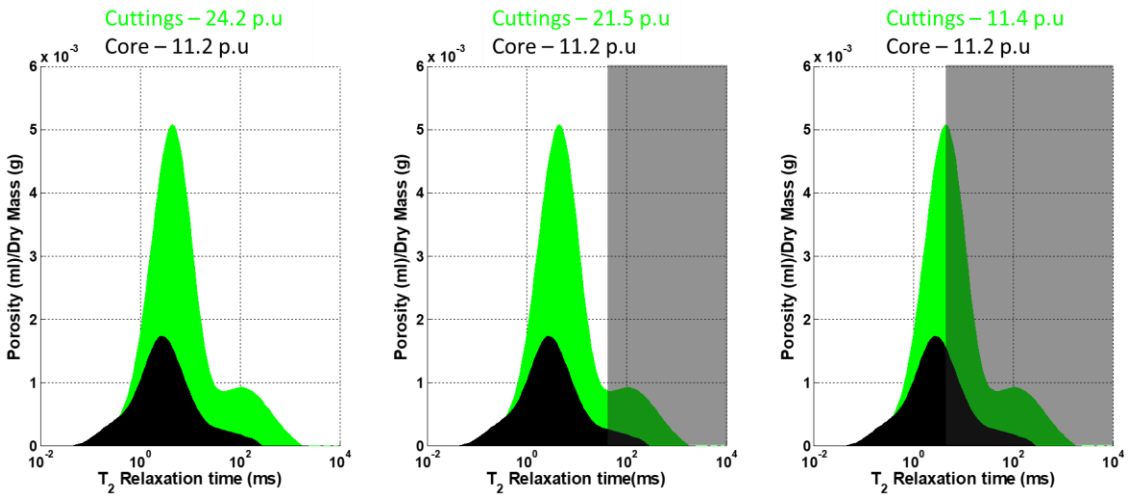

Fig. 4— T_2 distribution from a core plug (black trace) are compared with the distribution for cuttings (green trace). Prior to acquisition of the T_2 data, an effort was made to remove as much water from the surface of the cuttings via spinning it off in a centrifuge. The left panel shows that there is a significant overlap between the T_2 distribution of the core plug and that of the cuttings. The middle panel shows that if a T_2 cutoff near is applied near 50 ms, a porosity of 21.5 p.u. is derived which is still nearly double the porosity expected from the plug data. This indicates that this T_2 cutoff has not done an effective job at eliminating the signal from fluid on the surface of the cuttings. The right-hand panel shows where the T_2 cutoff would have to be applied to derive a porosity like that expected from the plug data. Clearly, applying the T_2 cutoff in this location makes no physical sense as it eliminates a significant portion of the signal within the pores of the sample.

The data presented in Figures 3 and 4 demonstrates that in order to derive the porosity of cuttings samples the fluid on the surface of the cuttings needs to be eliminated. As outlined previously, (Dick et al., 2017), we have spent a great deal of effort exploring the best way to derive porosity by eliminating fluid from the surface of cuttings samples without compromising the fluid within pores. This included many different procedures including paper towel drying, screening, washing and rinsing with D_2O, centrifugation, employing surfactants and sonication. In the end, a best practice procedure was developed which involves a combination of centrifugation and rinsing with D_2O was developed for eliminating fluid from the surface of cuttings. The remainder of this paper will outline a series of examples for deriving porosity, T_2 distributions and T_1-T_2 maps on a selection of different cutting samples. In addition, where possible the data derived from the cuttings' procedure will be compared with analogous data from other sources such as core plugs and NMR logs

EXPERIMENT

We have outlined our procedure for removing fluid from the surface of cuttings in detail previously (Dick et al., 2017, Dick et al., 2020, Dick et al., 2021), 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 T_2 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 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

RESULTS

Initial tests of the method for determining the porosity of cuttings were completed using Marcellus shale samples. In order to confirm the accuracy of the method, core plugs and cuttings from the same well at similar depths were obtained. The cutting samples were acquired from ten to thirty-foot spans in depth while the plugs were acquired within these spans. As shown in Figure 5, the porosity derived from the procedure for the cuttings agree well with the expected porosity from plugs. In general, the difference between the porosity derived from the cuttings and that determined from the plug was less than 1 p.u. Any difference in porosity derived from the plug and that derived for the cuttings could be attributed to inhomogeneity in the porosity of the field and the fact that the cuttings provide an average porosity over a range of depths while the core plugs provide a single porosity at a fixed depth.

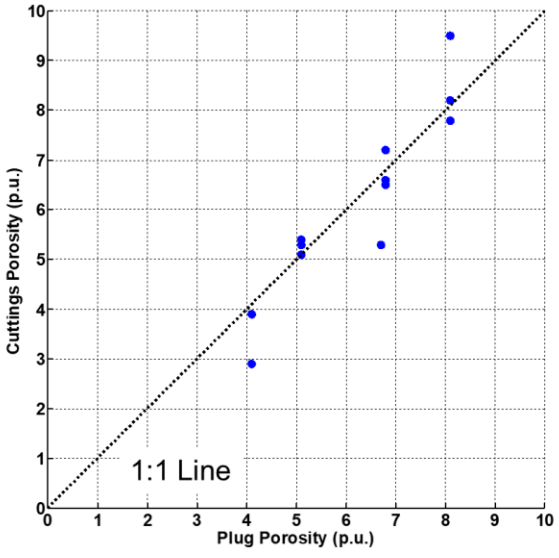

Fig.-5— A comparison between the porosity derived from the cuttings sample with the expected porosity from core plugs is shown. The core plugs and cuttings were from the same well at similar depths. The cutting samples were acquired from ten to thirty-foot spans in depth while the plugs were acquired within these spans. In general, the difference between the porosity derived from the cuttings and that determined from the plug was less than 1 p.u.

Because cuttings are less susceptible to the inhomogeneity of the well than core samples, a better assessment is to compare the porosity derived from cuttings to that determined via NMR logging. In NMR logging, the porosity is sampled multiple times per foot of depth. These porosity measurements can then be averaged into depth allotments to match the range of depth from which the cuttings were retrieved. Figures 6 and 7 show a comparison between the porosity derived from NMR logging and that determined from the cuttings retrieved from the same well. The well was located in Ward County Texas and the log and cuttings data sampled Bone Spring and Wolfcamp formations. For this well, the porosity was sampled every 6 inches (Figure 6 and 7 – blue trace) via the NMR log. The data was then averaged in 10-foot allotments (Figures 6 and 7 – red trace) to match the cuttings. The porosity from forty-two cutting samples were measured (Figure 6 and 7 – green dots) and compared with the porosity determined by the NMR log. In addition to the log data and cuttings samples, eleven core plugs were also available for further validation of the porosity data (Figure 6 and 7 – black dots). Total porosity measured from the forty-two cuttings samples in the range from 4.0 to 12.1 p.u. while the NMR on core plugs from the same depth interval ranges from 1.3 p.u. to 11.2 p.u. and the NMR log ranges from 5.2 p.u. to 12.7 p.u. porosity. While the porosity range from cuttings and core plugs are similar to the porosity range from NMR log, on average a 1.6 p.u. porosity difference exists between cuttings and NMR log and a 4.5 p.u. porosity difference occurs between core plugs and NMR log. Clearly, the

cuttings did a better job matching the porosity determined by the log as compared to the plugs. This is most evident in between 11000 ft and 11100 ft (Figure 6) where there are clearly three plug-based porosity measurements which are considerably lower than the log.

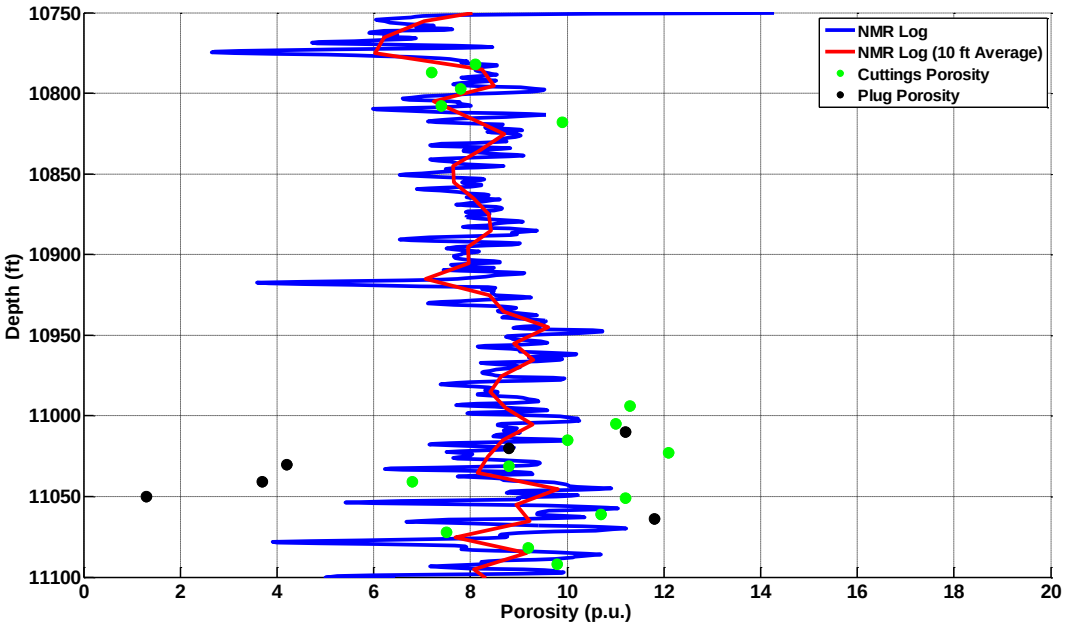

Fig. 6— A comparison between the porosity derived from NMR logging and that determined from the cuttings retrieved from the same well. For this well, the porosity was sampled every 6 inches (Blue trace) via the NMR log. The data was then averaged in 10-foot allotments (Ted trace) to match the cuttings. The porosity from 16 cutting samples were measured (green dots) and compared with the porosity determined by the NMR log. In addition to the log data and cuttings samples, 6 core plugs were also available for further validation of the porosity data (black dots).

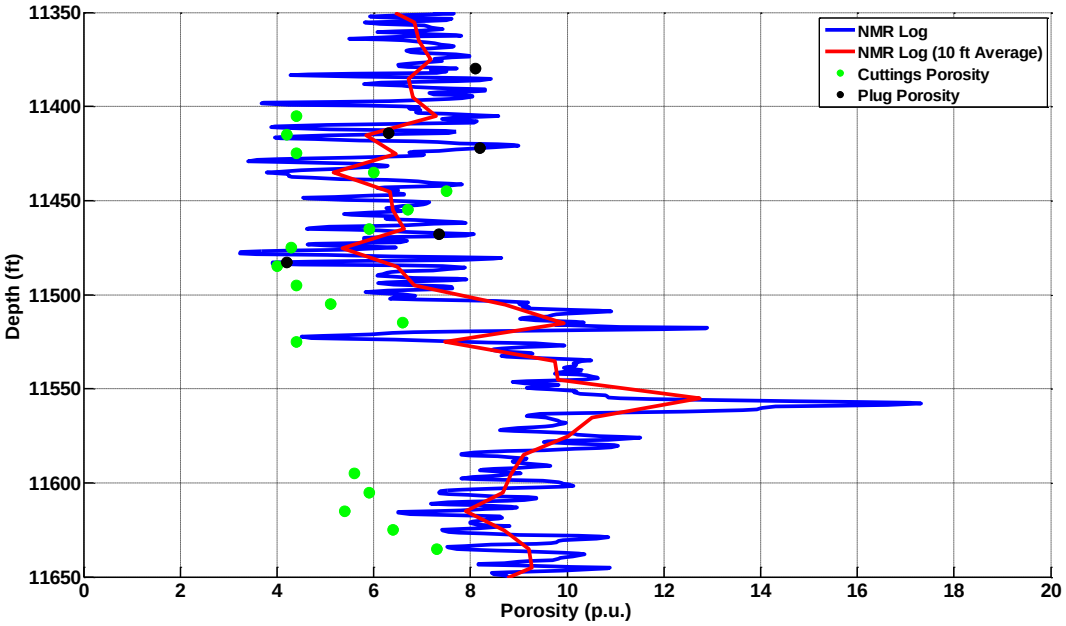

Fig. 7— A comparison between the porosity derived from NMR logging and that determined from the cuttings retrieved from the same well. For this well, the porosity was sampled every 6 inches (Blue trace) via the NMR log. The data was then averaged in 10-foot allotments (Ted trace) to match the cuttings. The porosity from 18 cutting samples were measured (green dots) and compared with the porosity determined by the NMR log. In addition to the log data and cuttings samples, 5 core plugs were also available for further validation of the porosity data (black dots).

Beyond determining porosity only, what makes our measurement unique is that the pore size (related to T_2) distributions of the cutting samples can also be determined. 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. To determine the accuracy of the T_2 distribution retrieved from the cutting's samples, a comparison was made with T_2 distributions retrieved from core data retrieved from the same well as the cuttings. In this case, all samples came from one well and were located in the Woodford formation. A 4" whole core was taken and sampled at a density of 5 ft spacing. Plugs from similar depths as the cuttings were provided for verification of the results. The porosity and pore size distributions for the plugs were probed using the same NMR parameters as those employed for the cuttings (Table 1). These data were then compared with the porosity and pore size distribution derived from PDC drill bit cuttings that came up the mud system from the approximate depth of the plugs.

Figure 8 shows the pore size distributions for plug 3Ha (black trace) retrieved at a depth of 9556.4 ft and plug 3Hb (brown trace) retrieved at a depth of 9556.95 ft. Also shown are the pore size distributions for cuttings at depths of 9550 ft (blue trace) and 9560 ft (red trace). Note that the NMR signal has been normalized to dry mass to facilitate comparison of the T_2 distributions. The porosity of the plug samples agreed well with that derived for the cuttings. The porosity of the 3Ha and 3Hb plugs were 1.6 p.u. and 2.0 p.u respectively while the porosity of the cuttings samples were 1.27 p.u. (9550 ft) and 1.9 p.u. (9560 ft). This comparison was well within the 1 p.u. accuracy of the cuttings' measurement.

Further, there is excellent agreement between the pore size distributions of the plugs and the cuttings. There can be no contribution from surface fluid to the T_2 distributions of the plug samples so the good agreement with the T_2 distribution of the cuttings samples cements the argument that surface fluid has been fully removed from the cuttings. Delving deeper into the T_2 distributions, it is obvious that the distributions of the cuttings samples have shorter relaxation times than the plug samples. For example, the plug data have contributions from T_2 components as long as 1000 ms whereas the maximum T_2 components of the cuttings' samples are closer to 100 ms. This may be evidence that some of the largest pores (with the longest T_2 values) may have been compromised in the crushed cuttings samples. It also may explain, why the cuttings seem to have slightly lower porosity as compared to plug data. This is the type of information that can only be revealed from T_2 distributions and is not available from porosity values alone.

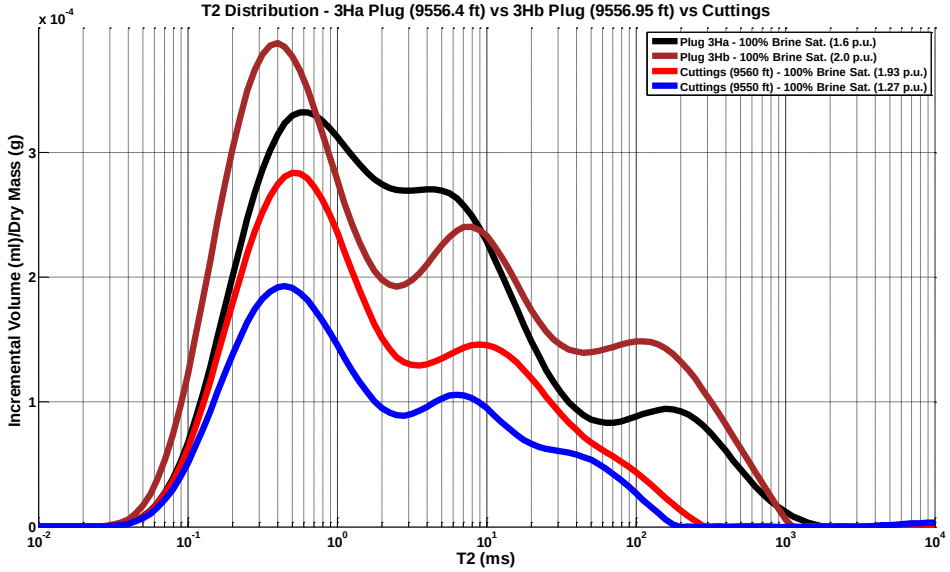

Fig. 8— The pore size distribution for plugs 3Ha (black trace) and 3Hb (brown trace) are compared with the distributions for cuttings at depths of 9560 (red trace) and 9550 (blue trace) feet. To normalize all the distributions on the same scale, the magnitude of the distributions is divided by the dry mass of the samples. The shape of each distribution is similar.

Having shown that fluid has been removed from the surface of the cuttings and that T_2 distributions retrieved for the cuttings are accurate, exploring the expansion of our cutting's measurement beyond porosity and pore size distribution was done. Specifically, expansion of the measurement to include T_1-T_2 maps was explored. 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 and T_1 and T_2 relaxation times differ with viscosity. For example, heavy organic fluids such as bitumen will have short T_2 relaxation times and long T_1 relaxation times and will appear in the upper left quadrant of a T_1-T_2 map. Conversely, clay bound water (CBW) and brine will have similar T_1 and T_2 relaxation times and 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 9 shows the T_1-T_2 maps for plug 3Hb (9556.95 ft) and cuttings at depth of 9560 ft. The T_2 distribution data was previously shown for these samples in Figure 8. The plug and cuttings maps are very similar with each showing content from heavy organics in the upper left quadrant. There is little signal in the other quadrants indicating little water or light hydrocarbons in the pores of the plug or cuttings. This is consistent with the low porosity determined for the cuttings and plug (1 – 2 p.u.).
.

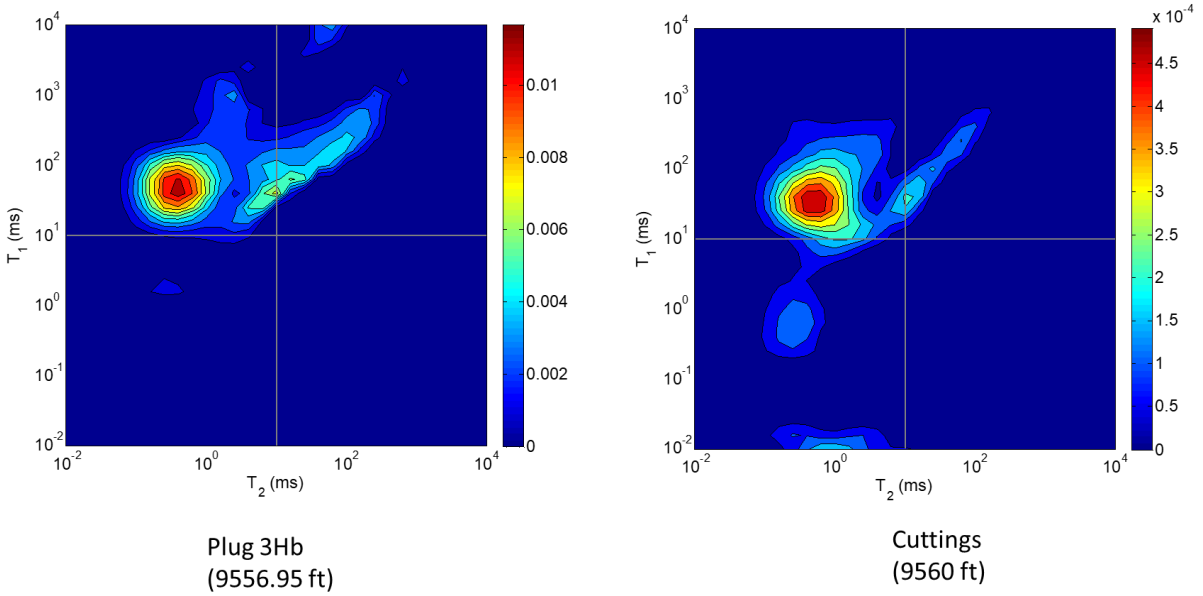

Fig. 9— The T_1-T_2 maps for plug 3Hb (9556.95 ft) and cuttings at depth of 9560 ft are shown. The maps are very similar with each showing content from heavy organics in the upper left quadrant. There is little clay bound or free water or light hydrocarbons in the plug or cuttings. This is consistent with the low porosity for determined for the cuttings and plug (1 – 2 p.u.).

CONCLUSIONS

We have successfully developed a method for determining the porosity of cuttings via NMR. There are two key factors to our porosity measurement. Firstly, we employ three independent NMR measurements to derive the bulk volume and hence the porosity of the cuttings. Employing only NMR data removes any uncertainty in the porosity determination which can arise when mass/density are employed to determine bulk volume. Secondly, we remove the fluid signal from the surface of the cuttings. This ensures that only NMR signal from fluid within the pores of the sample is observed. This eliminates any chance that NMR signal from fluid on the surface of the cuttings can be mistaken for pore volume leading to an overestimate of porosity.

We have tested hundreds of samples from various unconventional formations including Utica, Marcellus, Woodford, Bone Spring, Wolfcamp, Niobrara and Turner. Our measurement needs just 0.5 to 3 g of cuttings sample and takes less than 10 mins to complete.

In addition, it works on samples down to 1/70" (360 μm) in size. This ensures that the porosity can be determined for cuttings samples drilled with Polycrystalline diamond compact bits.

While our work has focused primarily on unconventional reservoirs to date, we are currently looking at expanding our measurement to conventional samples. We have developed a modified version of our procedure for the elimination of NMR signal from surface fluid. This modified procedure employs only centrifugation at lower speeds and does not require rinsing with D_2O. To date, we have successfully determined the porosity of Nugget, Carbon Tan and Buff Berea sandstone as well as Indiana limestone crushed core (or pseudo cutting) samples. In the future, we will test the measurement on real cuttings samples.

ACKNOWLEDGMENTS

The authors thank Continental Resources, EPOCH Consulting LLC, Grayson Mill Energy, and Premier Oilfield Group for providing samples and data as well as discussions.

NOMENCLATURE

Abbreviations

NMR = nuclear magnetic resonance
PDC = polycrystalline diamond compact
p.u. = porosity unit
CPMG = Carr-Purcell-Meiboom-Gill
IR-CPMG = Inversion Recovery – CPMG
HC = Hydrocarbon
Tau = One half spacing between echoes in CPMG pulse sequence.

Symbols

T_1 = longitudinal relaxation time
T_2 = transverse relaxation time
V_{Total} = total volume of sample tube
V_{pore} = pore volume of sample
$V_{pore+fluid}$ = volume of fluid in a sample tube partially filled with brine and pore volume of saturated cuttings

REFERENCES

Althaus, S. M., Chen, J.-H. and Zhang, J., 2019, NMR Measurement Of Porosity And Density From Drill Cuttings Of Unconventional Tight Reservoirs, Paper presented at SPWLA 60th Annual Logging Symposium, The Woodlands, Tx, USA, 17–19 June.

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

Dang, S. T., Rolke, M. M., Sondergeld, C. H. and Rai, C. S., 2017, Study of Drill Cuttings Porosity For Formation Evaluation, Paper SCA2017-075 presented at the International Symposium of the Society of Core Analysts, Vienna, Austria, 27 August – 1 September.

Dick, M. J., Green, D., Kenney, T., Veselinovic, D., Tallarita, J. and Smith, M.A., 2017, Quick and Simple Porosity Measurement at the Well Site, Paper SCA2017-013 presented at the International Symposium of the Society of Core Analysts, Vienna, Austria, 27 August – 1 September.

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

Dick, M.J., Veselinovic, D., Kenney, T., Green, D., Haecker, A. and Boyce, M., 2021, T1-T2 NMR on Shale Cuttings, Paper 5500 presented at the Unconventional Resources Technology Conference, Denver, CO, USA, 26-28 July.

Ganser, N., Wittman, B., Hemenway, M., Dick, M., Veselinovic, D., Kenney, T., Green, D. and Rowe, H., 2020, Integration of Geochemical and Petrophysical Measurements from Drill Cuttings for Unconventional Reservoir Characterization, Converse County, Powder River Basin, Paper 3290 presented at the Unconventional Resources Technology Conference, Houston, TX, USA, 20-22 July.

Mitchell, J., Valori, A. and Fordham, E.J., 2019, A robust nuclear magnetic resonance workflow for quantitative determination of petrophysical properties from drill cuttings., *Journal of Petroleum Science and Engrineering*, **174**, 351-361.

Singer, G., Flaum, M., Chen, S. and Ma, S. M., 2021, NMR Drill Cutting Analysis- Methodology Evaluation and Operational Best Practices, Paper presented at the SPWLA 62nd Annual Logging Symposium, 17–20 May.

ABOUT THE AUTHORS

Mike Dick has a Bachelor of Science degree from the University of New Brunswick. His post-graduate work focused primarily on molecular physics and included both a Master's degree from the University of New Brunswick and a Ph.D. from the University of Waterloo. After graduation, Mike's career diversified working first in astrophysics while doing a post-doctoral fellowship at NASA's Jet Propulsion Lab. Following this position, Mike moved into the field of nuclear physics in Chalk River Ontario with Bubble Technology Industries (BTI)

as a research scientist. His work with BTI focused primarily on developing unique radiation detectors for defense and homeland security organizations, first responders, space agencies, regulatory/standards groups, and research institutions. This work has resulted in three patent filings. Mike joined the Green Imaging Technologies in September 2015 as a Principal Research Scientist. Mike works at innovating new NMR techniques and tools for our clients.

Dragan Veselinovic is the Senior Applications Specialist for Green Imaging Technologies. He holds a Master's of Science in Physics degree from the University of New Brunswick. He has worked in several capacities at GIT, which has allowed him to become the "Go To" person for GIT customers. Dragan conducts research, manages the laboratory, and trains all new customers. He also plays an important role in many of the research and development projects undertaken by GIT.

Taylor Kenney has a Bachelor of Science degree from the University of New Brunswick focusing primarily on microbiology. After graduation Taylor's interests diversified and subsequently started off his career at H2 Laboratories in 2014 (Division of Green Imaging Technologies) and continues to build out his knowledge and expertise in core analysis and reservoir characterization 8 years later. As the Lab Manager, Taylor is responsible for all petrophysical core analysis and technical reporting for H2 Laboratories; he also participates regularly in novel research and scientific writing in association with Green Imaging Technologies, having co-authored 4 research papers as well as playing an integral part in work that's led to 2 patent filings.

Derrick Green holds a Bachelor of Science and a Ph.D. in Electrical Engineering from the University of New Brunswick. After graduation, Derrick worked as a Senior Research Scientist for a major medical MRI manufacturer in Cleveland, Ohio (Philips Medical Systems) where he filed his first patent. His focus at Philips was software product development, designing complex MRI measurement techniques. He was responsible for the life cycle management of Philips software and introduced quality control systems that allow them to become ISO9000 certified. Derrick is also the co-founder of Green Imaging Technologies and has acted as the company's Chief Technical Officer since incorporated in 2005. His technical expertise has allowed GIT product offerings to increase significantly, as is evidenced by his over 30 peer-reviewed publications and five patent filings.