

## Evaluation of NMR parameters for porosimetry of sandstones

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### SUMMARY

In this laboratory study we examine the relationship between NMR relaxation times and parameters describing the pore geometry of sandstones. Using measurements on 45 cores spanning fourteen geological formations, we compare characteristic relaxation times determined from the NMR relaxation time distribution, including the mean log relaxation time, the median relaxation time, and the peak relaxation time, to characteristic pore geometry parameters, including the surface-area-to-volume ratio, the median pore size, and the peak pore size. Our objective is to determine which characteristic NMR relaxation times best correlate to which parameters describing the pore geometry. By improving our ability to model characteristic pore geometries, we can build better models of permeability using NMR data.

Our results show that for samples with little to no iron oxide, the mean-log relaxation time correlates with the surface-area-to-pore-volume ratio while the median and peak relaxation times correlate well with the median and peak pore size, respectively. When we consider a range of iron oxide rich cores the petrophysical relationships become more complex and we must consider developing separate petrophysical models for cores with different mineralogies.

**Key words:** NMR, MICP, BET, porosimetry

### INTRODUCTION

Determining hydraulic properties of porous geological materials using geophysical methods is a well-established practice in the oil industry; however, the practice is still new in hydrogeological and environmental applications. Nuclear magnetic resonance (NMR) can be used to estimate pore size and permeability due to its sensitivity to water content and pore geometry. The petrophysical transform used relates a characteristic NMR transverse relaxation time ( $T_2$ ) to the pore radius ( $R$ ), which for ideal shapes is related to the surface-area-to-volume ratio ( $S/V = S_{por} = \alpha R^{-1}$ ):

$$T_2^{-1} = \rho_2 \alpha R^{-1} = \rho_2 S_{por}, \quad (1)$$

where  $\alpha$  is a shape factor such that  $\alpha = 1$  for planar pores, 2 for cylindrical pores, and 3 for spherical pores, and  $\rho_2$  is the surface relaxivity, which accounts for the ability of a pore surface to enhance relaxation (Brownstein and Tarr, 1979). Equation 1 assumes that relaxation occurs in the fast diffusion regime, which has been shown to be true for a wide range of sandstones (Kleinberg and Horsfield, 1990). Since  $S_{por}$  and  $R$

are linked to hydraulic properties such as permeability (Thompson et al., 1987), Equation 1 implies that NMR measurements can be used to estimate permeability.

Many studies have examined at the relationship between  $S_{por}$  and the mean-log relaxation time ( $T_{2ml}$ ) (e.g., Dunn et al., 1999) or between  $R$  and  $T_{2ml}$  (e.g., Matthews et al., 2006). Furthermore, it has been shown that, under the fast diffusion assumption, the NMR relaxation time distribution ( $T_2$ -distribution) is a linear function of the grain size distribution (Keating and Falzone, 2013) and is closely related to the pore size distribution determined from mercury injection capillary pressure (MICP) measurements (e.g., Stingaciu et al., 2010). However, despite the considerable body of work linking NMR relaxation times to pore geometries, there is some disagreement about which pore geometry parameters are best estimated by the NMR measurement. In this study we systematically evaluate the relationship between NMR relaxation times and characteristic pore geometries.

In order to determine which NMR parameters correlate with which geometric parameters, we characterized the pore and NMR properties of sandstone cores. We consider four NMR relaxation times that characterize the  $T_2$ -distribution:  $T_{2ml}$ , the tenth percentile relaxation time ( $T_{2(10)}$ ), the median relaxation time ( $T_{2med}$ ) and peak amplitude relaxation time ( $T_{2p}$ ). We then compare these characteristic relaxation times to parameters that characterize the pore-geometry including:  $S_{por}$ , the tenth percentile pore diameter by volume ( $R_{10}$ ), the median pore diameter by volume ( $R_{med}$ ), and the peak pore size ( $R_p$ ).  $R_{med}$  and  $R_p$  were selected as representative pore geometries representing the dominant pore sizes while  $R_{10}$  was chosen to represent small pores which may restrict fluid flow. Ultimately, understanding the geometric parameter that best controls the NMR relaxation time behavior, will allow us to build more robust models of permeability.

### METHODS

Laboratory NMR measurements were collected on 45 sandstone cores from fourteen different formations. The sandstones were chosen to include a wide range of pore geometries and permeabilities; the median pore size varies over two orders of magnitude, and the measured permeabilities range over six orders of magnitude. By visual inspection, we determine that the Sherwood sandstones have high iron-oxide content, indicated by the red color of the cores. Mineralogical analysis and visual inspection of the other cores suggest that iron oxide minerals are not present in significant amounts in the rest of the cores analyzed.

Prior to saturation, all samples were oven dried and placed under a vacuum in order to remove all gasses from the pore space. The samples were then saturated with a 10 mS/m sodium chloride brine. Gravimetric porosity was determined

for all samples from the difference between the saturated and unsaturated masses of each core.

MICP data were used to determine the distribution of pore-throat sizes in the cores. MICP data acquisition involves the incremental injection of mercury into a small porous sample under increasing pressure, ranging from, e.g., 3.4 kPa to 206.8 kPa. The amount of Hg injected is used to determine the total volume of the pores filled at that pressure. The size of the pores is then estimated using the Washburn equation (Washburn, 1921). The surface area of the cores was determined using the BET method with nitrogen as the adsorbing gas (Brunauer et al., 1938). To measure the surface area nitrogen gas is injected into the sample at increasing pressures and the partial pressure is measured at each step; the resulting BET isotherm is then used to determine the quantity of nitrogen adsorbed to the surface of the sample. The BET method determines the specific surface area which is used to determine  $S_{por}$ . NMR measurements were made with a 2 MHz Rock Core Analyzer (Magritek Ltd) using a CPMG pulse sequence with a 200  $\mu$ s echo time. The data were inverted to produce  $T_2$  relaxation time distributions using a non-negative least squared inversion algorithm (Whittall et al., 1991).

## RESULTS AND DISCUSSION

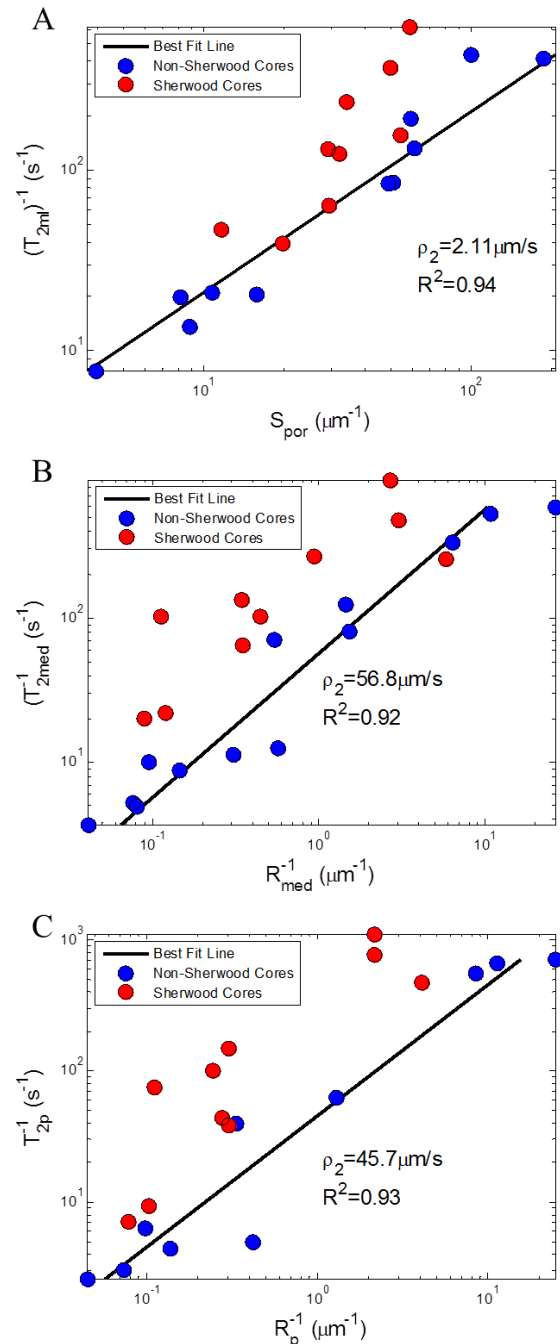
The characteristic pore geometry values  $S_{por}$  was calculated from the BET data; the values  $R_{10}$ ,  $R_{med}$ , and  $R_p$  were calculated from the MICP pore-throat size distribution.  $R_{10}$ ,  $R_{med}$ , and  $R_p$  are calculated from the MICP pore size distributions. The characteristic relaxation times  $T_{2ml}$ ,  $T_{2(10)}$ ,  $T_{2med}$ , and  $T_{2p}$  were calculated from the NMR relaxation time distribution.  $T_{2ml}$  is calculated from,

$$\log(T_{2ml}) = \sum_{i=1}^N A_i \log(T_{2i}) / \sum_{i=1}^N A_i, \quad (2)$$

where  $A_i$  is the inverted amplitude at relaxation time  $T_{2i}$ .  $T_{2(10)}$  is the value of the NMR distribution below which 10% of the total signal amplitude was contained.  $T_{2med}$  is the relaxation time at which half the total signal is above and half is below.  $T_{2p}$  is the relaxation time corresponding to the maximum  $A_i$  value. The characteristic pores sizes  $R_{10}$ ,  $R_{med}$ , and  $R_p$  are calculated from the MICP pore size distribution using the same methodology used to derive  $T_{2(10)}$ ,  $T_{2med}$ , and  $T_{2p}$  were derived from the NMR  $T_2$ -distribution, respectively.

In order to compare the characteristic NMR relaxation time data to the characteristic pore geometry we started by assuming that relaxation occurs in the fast diffusion regime and that Equation 2 is valid. The characteristic relaxation times and pore geometries were plotted on a log-log plot and the fits were evaluated using the  $R^2$  coefficient of determination. Note that the Sherwood cores were not included in this quantitative analysis due to their mineralogy.

The results from the linear regressions are summarized in Table 1. Based on these results we selected three of the relationships exhibiting the strongest  $R^2$ -values (highlighted in Table 1) and plotted the results:  $T_{2ml}$  versus  $S_{por}$  (Figure 1A),  $T_{2med}$  versus  $R_{med}$  (Figure 1B), and  $T_{2p}$  versus  $R_p$  (Figure 1C). In all figures the Sherwood cores, indicated by the red dots, were not included in the linear regression. The relationship between  $T_{2ml}$  and  $S_{por}$  works very well for the iron-oxide free samples. The Sherwood cores, however, appear to obey a



**Figure 1:** (A)  $T_{2ml}$  versus  $S_{por}$  (B)  $T_{2med}$  versus  $R_{med}$ , (C)  $T_{2p}$  versus  $R_p$ .

power-law relationship that suggests that the relaxation in these cores does not occur in the fast diffusion regime (Godefroy et al., 2001). The strong relationships seen between  $T_{2med}$  and  $R_{med}$  in Figure 1B and between  $T_{2p}$  and  $R_p$  in Figure 1C suggest that NMR data can be used to model the center of the pore size distribution very well.  $\alpha\rho_2$  calculated for  $R_{med}$  and  $R_p$  are very similar; since most of the samples tested had a single dominant pore size, the median and peak pore sizes were very similar. Therefore, it appears that either model would be an acceptable petrophysical transform. We note, as seen in Table 1, that  $T_{2(10)}$  does not model any pore geometries parameters well, and no NMR relaxation time value models  $R_{10}$  with any consistency. This suggests that, while the center of the NMR relaxation time and MICP pore size distributions are closely related, the two fail to correspond

at small relaxation times and pore sizes. We note that this difference may be due to differences in the sensitivity of the NMR relaxation time distribution and the MICP distribution; the NMR distribution is sensitive to the pore-size while the MICP distribution gives the distribution of pore-throats.

The Sherwood cores appear to follow separate petrophysical relationships depending on which characteristic pore geometry is used. In Figure 1A, the Sherwood cores appear to follow a power law relationship with  $S_{por}$ , which would suggest that the fast diffusion assumption underlying Equation 1 does not apply to these cores. In Figure 1B and 1C, the characteristic relaxation times for the Sherwood cores appear to follow a similar linear relationship as the iron-oxide free cores. An ongoing area of research is investigating how the characteristic pore geometry impacts measurements of surface relaxivity for iron-oxide rich sandstones. Further work will be needed to determine how pore geometry controls NMR relaxation in these samples before robust petrophysical transforms can be developed.

## CONCLUSIONS

NMR parameters that have been used to estimate characteristic pore geometries have been assessed here to determine which predictors work best for sandstones without paramagnetic impurities. Statistically,  $T_{2ml}$  does the best job of estimating  $S_{por}$ , although  $T_{2med}$  and  $T_{2p}$  estimate  $R_{med}$  and  $R_p$ , respectively, with almost equally good precision. On the other hand,  $T_{2(10)}$  did not predict any pore geometries well. From this we can conclude that the NMR  $T_2$ -distribution cannot be used to model the entire pore size distribution, only the center of the distribution. When considering a set of sandstones from the iron-oxide-rich Sherwood formation, it appears that the paramagnetic species influence how the NMR measurement is related to different pore geometries. Further data will be needed to construct robust petrophysical relationships for such iron-oxide rich sandstones.

## ACKNOWLEDGMENTS

The authors would like to acknowledge the contributions of Andrew Binley from Lancaster University, UK and Lee Slater from Rutgers, who provided many valuable insights. They would also like to acknowledge the data and materials contributed by Andrew Binley and Mejus Lakam from Lancaster University, UK, Quentin Fisher from the University of Leeds, UK, and Sabine Kruschwitz from the Technical University of Berlin. This research was based on work supported by the NSF under Grant No. 1246507. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not

necessarily reflect the views of the National Science Foundation.

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	$S_{por}$ ( $\mu\text{m}^{-1}$ )		$R_{10}$ ( $\mu\text{m}$ )		$R_{med}$ ( $\mu\text{m}$ )		$R_p$ ( $\mu\text{m}$ )	
	$\rho_2$ ( $\mu\text{m/s}$ )	$R^2$	$a\rho_2$ ( $\mu\text{m/s}$ )	$R^2$	$a\rho_2$ ( $\mu\text{m/s}$ )	$R^2$	$a\rho_2$ ( $\mu\text{m/s}$ )	$R^2$
$T_{2ml}$ (s)	2.11	0.94	0.71	-0.47	77.54	0.63	79.33	0.57
$T_{2(10)}$ (s)	48.39	-0.46	18.35	-0.09	2266.86	-4.58	2438.67	-36.59
$T_{2med}$ (s)	1.73	0.85	0.56	-0.32	56.84	0.92	60.36	0.90
$T_{2p}$ (s)	1.26	0.74	0.40	-0.17	40.04	0.92	45.66	0.93

**Table 1: Modeled surface relaxivities ( $\rho_2$ ) or shape factor multiplied by the surface relaxivity ( $a\rho_2$ ) and coefficients of determination for each NMR characteristic relaxation time. The Sherwood sandstone cores shown as red circles in Figure 1 were not included in the regression analysis. Shaded values correspond to the data plotted in Figures 1.**