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Calibration of NMR well logs from carbonate reservoirs with laboratory NMR measurements and μXRCT

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Abstract

The use of nuclear magnetic resonance (NMR) well log data has the potential to provide in-situ porosity, pore size distributions, and permeability of target carbonate CO_2 storage reservoirs. However, these methods which have been successfully applied to sandstones have yet to be completely validated for carbonate reservoirs. Here, we have taken an approach to validate NMR measurements of carbonate rock cores with independent measurements of permeability and pore surface area to volume (S/V) distributions using differential pressure measurements and micro X-ray computed tomography (μXRCT) imaging methods, respectively. We observe that using standard methods for determining permeability from NMR data incorrectly predicts these values by orders of magnitude. However, we do observe promise that NMR measurements provide reasonable estimates of pore S/V distributions, and with further independent measurements of the carbonate rock properties that universally applicable relationships between NMR measured properties may be developed for in-situ well logging applications of carbonate reservoirs.

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1. Introduction

Carbonate reservoirs are an important CO_2 storage resource in the United States. The CO_2 injection and storage capacity depend on the stratigraphic distribution of matrix pore space and connected and isolated large pores/vugs and fractures. The Kansas Geological Survey has collected and combined NMR, spectral sonic, and resistivity well

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logs to estimate the stratigraphic distribution and connectivity of matrix and macro porosity within the carbonate Arbuckle injection zone. The NMR well log holds the potential to provide a continuous record of porosity, pore size distributions, and permeability for this reservoir. The intensity of the NMR signal is directly proportional to the amount of fluid residing in the pores and can thus be used as a measure of porosity. This tool also measures the ^{1}H transverse relaxation time (T_2) of the fluid contained within the pore spaces of the surrounding rock. This relaxation causes an exponential decay in the measured NMR signal intensity as a function of time which can then be numerically inverted to produce a distribution of decay constants. The relaxation mechanism in this system is the collision of the fluid molecules (water) with the pore walls, and the more frequently these molecules interact with the pore surface the faster the signal decays. Therefore, a shorter T_2 corresponds to a smaller pore space and the T_2 can be generally related to the surface to volume ratio (S/V) and pore size distribution of the pore network with the following equation:

$$\frac{1}{T_2} = \rho \frac{S}{V} + \frac{1}{T_{2B}} \tag{1}$$

Where T_2 is the observed decay constant, T_{2B} is that of the bulk fluid water, and ρ is the surface relaxivity of the pore surface that relates to the ability of that material to induce T_2 relaxation. Using this equation the pore size distribution can be predicted assuming set pore geometry. Further, the T_2 measurements can be used to generate permeability estimates using equations such as the Schlumberger Doll Research (SDR) equation;

$$k = A \cdot T_{2LM}^2 \cdot \varphi^4 \tag{2}$$

This equation estimates permeability from the log mean of the T_2 distribution (T_{2LM}), the NMR measured porosity (φ), and an empirically derived constant *A*. In practice, the value for *A* is derived by fitting independently measured permeability of extracted cores to those predicted by the SDR method for those same cores, and varies substantially based on rock type. It should be noted that this equation is not related to the standard definition of permeability in Darcy's Law. It has been shown to be effective at predicting permeability of sandstone formations where pores are highly connected and there are clear relationships between porosity and permeability. These same relationships may not apply in carbonate reservoirs where pore sizes differ by orders of magnitude and can be well isolated. It is, therefore, unclear if these equations are suitable for defining permeability relationships in NMR well logs of carbonate rocks.

The work we present here is aimed at using independent measurements of permeability and S/V to determine the suitability of these relationships to adequately predict critical properties for carbonate reservoirs from NMR data. We have chosen to investigate a range of carbonate rock cores of varying lithology from the Weyburn-Middale CO_2 Monitoring and Storage Project Saskatchewan, Canada and the Arbuckle injection zone at the Wellington CO_2 storage demonstration site, Kansas. Here, we use differential pressure measurements to provide a direct measurement of permeability and μXRCT to directly probe the S/V ratio of the pore network. The results indicate that while the NMR estimated permeability values differ from the measured values by orders of magnitude within the same flow units, the S/V values estimated from NMR measurements align well with those extracted from μXRCT measurements. These results indicate that further work is required to further refine the equations needed to estimate permeability, and future directions for developing these relationships will be discussed.

2. Experimental

2.1. Permeability measurements

The permeability of each Weyburn core was determined by measurement of flow rates and corresponding

differential pressures, using 25°C synthetic brine at near-reservoir confining pressure (see Smith et al., [1], Figure 1 for a diagram of the flow assembly). Core samples were fitted with tubing endcaps at each end and encased in heat-shrinkable fluorelastomer tubing to create an impermeable barrier between the sample brine and the water in the pressure vessel. Sample assemblies were plumbed into inlet and outlet fluid lines (each with independent pressure transducers) which passed through the head of the pressure vessel. During measurements, a dedicated syringe pump maintained a constant confining pressure of 24.8 MPa/3600 psi within the vessel, while a separate dual-cylinder pump delivered brine to the sample at desired flow rates. A back-pressure regulator imposed an outlet pressure of 12.4 MPa/1800 psi to mimic in-situ reservoir conditions. At least 5 measurements per sample were used to compute permeability, k, according to:

$$k = (Q \cdot \mu \cdot L_c) \cdot (A_c \cdot \Delta P)^{-1} \quad (3)$$

where Q is volumetric flow rate; μ is brine viscosity; ΔP is differential pressure across the core; and L_c, A_c are core dimensions length and cross-sectional area. Where possible, flow rates were varied over at least one order of magnitude for more robust determinations.

2.2. NMR measurements

The saturated Weyburn cores were placed into a Bruker microimaging probe and ^{1}H T_2 decays measured using a Carr-Purcell-Meiboom-Gill (CPMG) pulse sequence on a 400 MHz Bruker Avance spectrometer. The high field allows for high quality, low noise decays to be measured quickly. The T_2 distributions were generated by inverting the decay curves using standard Tikhonov regularization methods. A 5 ml aliquot of the saturating brine was also measured in order to provide a calibration for the NMR porosity measurements, and to obtain a bulk T_2 value for the brine (T_{2B} = 380 ms). Additional large diameter cores from the Arbuckle Dolostone, Wellington Kansas were analysed at Green Imaging where ^{1}H T_2 decays were measured at 2 MHz. At this lower field strength the measured T_2 values will be longer than those measured at the higher field strength since these values will scale by field. Permeabilty values were estimated using the SDR equation (Equation 2) use a standard value of 1×10^{-10} m^2s^{-2} for carbonate rocks [2, 3].

2.3. μXRCT Measurements

The μXRCT images for the Weyburn cores were collected at the Advanced Light Source on the 8.3.2 beamline at a resolution of 4.5 μm. Core stack resolution was decreased to a more computationally manageable 9 μm before further processing. The images were first processed with a median filter to remove image noise, and thresholded at a greyscales that most appropriately captured the voxels associated with the pores. These binary images were further eroded and dilated to remove additional spurious voxels arising from residual noise. The following algorithm was used in order to measure the S/V ratio of the binary images in three dimensions and is illustrated visually in Figure 1.

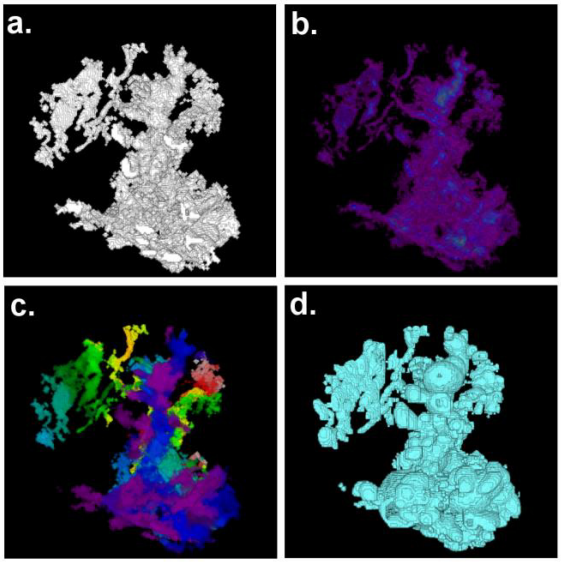

Fig. 1. a. Initial segmented pore body ; b. Squared Euclidean distance map where purple indicates pores close to the background and yellow and red indicate those further away; c. Segmented pore bodies labeled with different colors; d. Final segmented pore bodies fit to ellipsoids

- The binary images were transformed into a squared Euclidian distance map where each pore voxel is represented by its integer distance from the background voxels.
- A maximum image filter was applied and the local maxima were extracted.
- The maxima were used as seed points for a watershed transform that segmented the image into individual pores.
- The segmented pores were then fit with ellipsoids, and the surface area and volumes of the fitted ellipsoids extracted.

Given the large size of these XRCT image sequences the above algorithm was performed sequentially on smaller sub-volumes. Within these sub-volumes individual isolated pore networks were identified using a two-pass connected component labelling algorithm and the S/V ratios extracted. The main flaw with this approach is that the derivation of the initial sub-volumes is blind to sectioning individual pore networks into neighbouring volumes. However, if we use large enough subvolumes the pores are well separated at the resolution of the images and the chances of subdividing a pore into neighbouring sections is less likely. With the above methods it is possible to generate and compare S/V distributions over a range of resolutions.

3. Results

3.1. T_2 Distributions

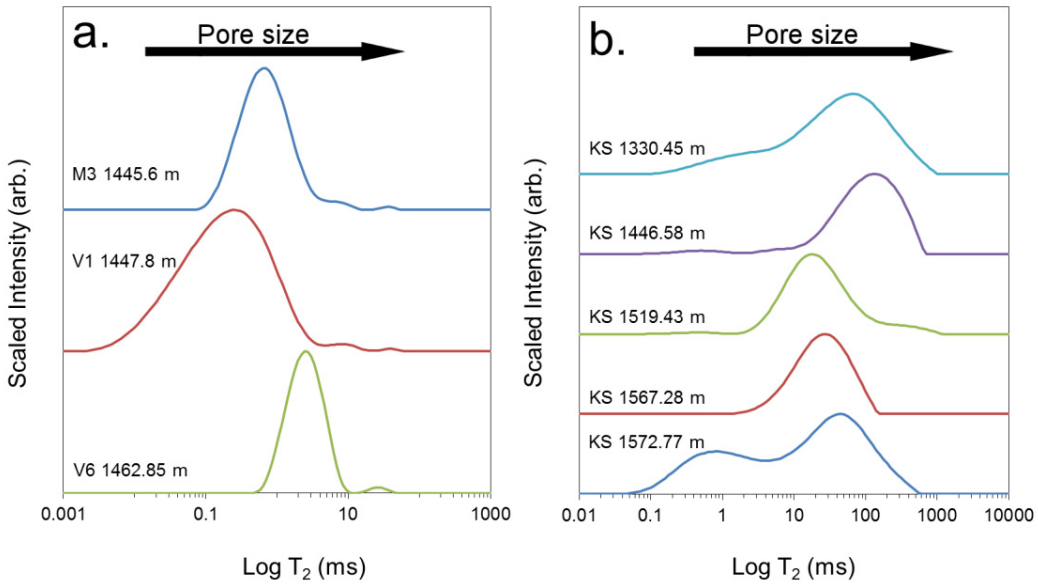

Fig. 2. T_2 distributions for a. selected cores from the Weyburn data set and b. the large Arbukle cores as a function of depth.

The T_2 distributions obtained from the NMR measurements (Figure 2) show a clear difference among the sample studied. In general, the T_2 distributions can be interpreted with larger pores being represented by larger T_2 values. For the Weyburn cores, it can be seen that the V6 limestones contain the largest pores compared with the M3 dolostone and the V1 limestone samples. The V1 core has a much larger distribution of pore sizes as well as much smaller pores. The pore distributions in the Arbuckle cores have broader distributions than the Weyburn samples and show some samples with clear bimodal distribution of pores. The longer T_2 values of the Arbuckle cores are in part due to the lower field strength used to collect the NMR data.

3.2. Permeability Measurements

Table 1. NMR measured porosity, log mean T_2 and predicted permeability values along with measured permeability values for the Weyburn cores

Sample	**M3 1445.6**	**M3 1445.9-2**	**V1 1447.8**	**V1 1448.1**	**V6 1462.75**	**V6 1462.85**	**V6 1463.2**
A (m^2s^{-2})	$1.00E\times10^{-10}$	$1.00E\times10^{-10}$	1.00×10^{-10}	1.00×10^{-10}	$1.00E\times10^{-10}$	$1.00E\times10^{-10}$	$1.00E\times10^{-10}$
Porosity (%)	41.0	42.0	21.5	21.6	31.2	16.5	20.0
T_{2LM} (ms)	0.71	1.04	0.11	0.14	2.53	2.54	1.23
k pred. (mD) SDR	0.140	0.332	2.53×10^{-4}	4.26×10^{-4}	0.597	0.247	2.40×10^{-2}
k meas. (mD)	1.92	5.50	3.90×10^{-2}	2.27×10^{-2}	7.00×10^{-2}	7.60×10^{-2}	5.60×10^{-2}

Table 2. NMR measured porosity, log mean T_2 and predicted permeability values for the Arbuckle Dolostone cores.

Sample	KS 1330.44	KS 1446.58	KS 1516.43	KS 1567.28	KS 1572.77
A (m^2s^{-2})	$1.00E\times10^{-10}$	$1.00E\times10^{-10}$	1.00×10^{-10}	1.00×10^{-10}	$1.00E\times10^{-10}$
Porosity (%)	2.7	8.1	6.0	8.1	5.2
T_{2LM} (ms)	31.7	83.8	22.6	23.2	5.3
k pred. (mD) SDR	5.27×10^{-3}	2.98	2.03×10^{-4}	0.239	2.03×10^{-3}

The results of the SDR calibrated permeability measurements are given for the Weyburn cores in Table 1 and the Arbuckle cores in Table 2. Comparing the measured and predicted (Eqn 2) permeability for the Weyburn cores shows that the SDR equation using an *A* value of 1×10^{-10} m^2s^{-2} incorrectly predicts permeability by as much as three orders of magnitude. The values for the V6 limestones and the Marly dolostones are off only by one order of magnitude in either direction, but those for the V1 limestones are off by upwards of three orders of magnitude. Since these cores were derived from the same well core it is clear that an *A* value that suitably predicts the permeability for one carbonate flow unit in a stratigraphic sequence may significantly differ from other carbonate flow units within the same reservoir. We also see that T_{2LM} values for the V1 and V6 rock types vary significantly, but their measured permeabilities are similar. This result cannot be simply attributed to differences in lithology since the V1 and V6 rocks have similar carbonate compositions. Variability of the *A* value is further illustrated for the cores from the Arbuckle Dolostone (Table 2) where the NMR extracted permeability varies over three orders of magnitude just within the injection zone (samples KS 1446.58, 1519.43, 1567.28 and 1572.77) In order to apply the NMR well logs as a measure of downhole permeability, the *A* value needs to be calibrated for each rock type in a cores section at minimum. We are further exploring intrinsic parameters with the empirical term to provide a deeper understanding behind the permeability and porosity relationships in the hopes of developing a more universal equation to extract permeability from NMR data for carbonate rocks.

3.3. μXRCT derived S/V distributions

Above, we observed that the NMR measured properties of the carbonate rock cores were poor indicators for the measured permeability. Here, we aim to see if there are measurable properties of these carbonate rocks which can be adequately described by the NMR measurements. Given that carbonate rocks can have pore geometries that deviate significantly for either cylindrical or spherical pore geometries it is unclear if relationship shown in equation 1 can be used to provide realistic measures of S/V. Towards understanding this relationship, we have developed methods to derive surface area to volume (S/V) ratios from μXRCT data. As is clear in Figure 1a, the pores developed in carbonate rocks have complex geometries and pore networks, and it is important to determine the appropriate pore geometries for these networks. In this work, we have used ellipsoids in order to determine appropriate pore statistics.

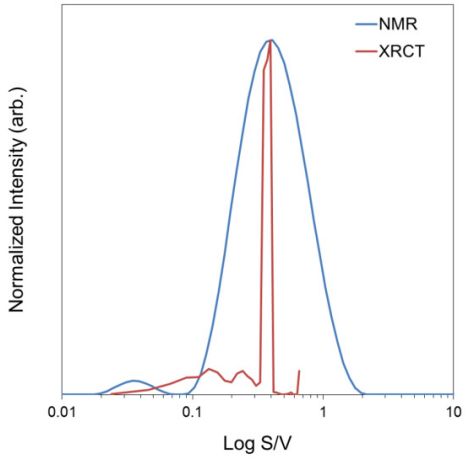

Fig. 3. S/V distributions obtained from NMR using equation 3 (blue) and directly calculated from the μXRCT results (red)

Our preliminary results from μXRCT on the V6 1462.85 sample produce a sharper distribution of S/V values than those derived from the NMR measurements. This result is likely related to the limitations of the T_2 inversion method where the regularization technique broadens and smooths the data. However, if we use a ρ value of 1 μm/s in equation 1 these distributions overlay well. This match indicates that the μXRCT data used is able to capture the majority of the pores that control the permeability in the V6 cores. However, the V6 samples have the largest pores of the Weyburn samples. It is possible that at a 9 μm voxel resolution we are not able to capture the smaller pores in the V1 and M3 samples that may control the permeability. Further work with higher resolution data sets will be required in order to determine at what scale the necessary parameters for the permeability calibrations can be adequately obtained for all flow units.

4. Conclusions

The work presented here indicates that the current methods for deriving permeability estimates from NMR data are poor indicators of the measured values using equations developed for homogeneous sandstones. At a fundamental level the results indicate that the NMR measurements are a good measure of the S/V as indicated by the agreement of the median NMR derived values with μXRCT results. Moving forward the progress will be focused on developing NMR permeability relationships using independent measurable properties of the carbonate rock cores beyond simple T_2 and porosity measurements. Prior work on fine grained sediments correlating the permeability and porosity relationships presented in the Kozeny-Carmen equations with those of the SDR equation indicate that the *A* value in the SDR equation can be deconstructed in measurable properties of the rock core such as tortuousity, pore shape factor, and surface relaxtivity [4,5]. Properties such as tortuosity and pore shape factor can be potentially extracted from the current μXRCT data sets collected for these cores, and future work will be focused on integrating these data into the NMR permeability models. However, it is also important to note that our own previous work on these same Weyburn rocks has shown a higher order porosity dependency of the permeability than predicted by the Kozeny-Carmen relationship in reactive core-flood experiments [6], and care will be required to adequately capture these relationships in any general equation to extract permeability values for carbonate rock from NMR well logs.

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