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Rock-typing of Laminated Sandstones by Nuclear Magnetic Resonance in the Presence of Diffusion Coupling

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Abstract

In this work, the aim is to assess the relative importance of the impact of diffusional coupling on NMR measurements of saturated laminated sandstone numerically at the layer scale to assess the feasibility of NMR rock-typing approaches. We use two 3D model structures based on a Boolean particle process, providing a range of structural to diffusion length ratios to explore the relationships between pore geometry, surface magnetic properties, and NMR transverse relaxation time. The influence of surface relaxivity and bulk susceptibility contrast on T_2 relaxation responses is tested for layered structures to improve the rock-typing methodology. An escalation in pore coupling is observed with decreasing bed thickness as well as decreasing bulk susceptibility contrast and surface relaxivity the latter ones reducing the time available for pore coupling by reducing the effective relaxation rate. When pore coupling is strong, the T_2 distribution clearly misrepresents the underlying bimodal distribution of the different morphologies. Consequently, the bimodal relaxation time becomes merged and the relative amplitude of the peaks fails to reflect the true morphologies of the models. Furthermore, we observed that in low noise conditions of numerical simulation the effect of diffusional coupling on transverse relaxation may be misinterpreted for the regularization effect on ILT solution. In such cases, careful selection of Laplace inversion method is essential for effective rock-typing by NMR.

Keywords Diffusion coupling, NMR, rock-typing, surface relaxivity, bulk susceptibility

1. Introduction

Quantitative interpretation of NMR responses in the presence of diffusional coupling between existing pore scales is a long standing problem in formation evaluation. Magnetization exchange may violate the main assumption necessary to relate a transverse relaxation rate to pore size. For materials strongly affected by diffusion coupling, the acquired relaxation time distribution reflects a complicated averaging of the pore structure which is difficult to interpret. Thus, understanding conditions and factors controlling coupling processes and effects on relaxation is essential for successful interpretation of NMR data. When standard assumptions hold, NMR provides valuable estimates of key reservoir properties including permeability, irreducible and mobile fluid fractions. Classification of relaxation regimes based on diffusional, dephasing and pore-scale ratios proposed by Hürlimann *et al*. (1995) suggests three asymptotic regimes: motional averaging (restricted diffusion), localization, and free diffusion [3]. Thus, understanding the conditions controlling coupling processes and their effect on the NMR relaxation response is clearly necessary to the successful utilization of NMR tool in petrophysical applications.

In several studies, the researchers have probed this impact theoretically and experimentally utilizing idealized pore networks models to understand how factors such as pore structure and surface geochemical reaction may affect the level of pore coupling [1, 2, 5]. Toumelin *et al*. (2002), Vincent *et al.* (2011) have shown that diffusion coupling may have a detrimental effect on interpretation of NMR responses of carbonates [1, 4]. Theoretical and experimental studies performed by Anand and Hirasaki (2007) consider the geometric controls on pore coupling in sandstones and grainstones [5]. Experimental study on silica gels with various Fe^{3+} content performed by Grunewald and Keating (2009) demonstrated that the influence of surface geochemistry of dual-porosity, micro- and macroporosity, in well-connected system can be a significant factor defining the strength of pore coupling [6].

In this work we aim to assess the impact and the relative strength of the diffusional coupling effects caused by surface relaxivity and susceptibility induced internal gradients on T_2 relaxation responses of a saturated layered porous systems. We construct a number of 3D numerical morphologies models based on Boolean particle processes to test the relationships between pore geometry, surface magnetic properties and NMR T_2 relaxation [7] and obtain the T_2 relaxation time distribution via lattice random walk simulations [8]. Furthermore, we the sensitivity of the results to changes in the Laplace inversion parameters.

2. Methodology

A set of 3D models of two morphological structures with different grain sizes were deployed based on a Boolean particle process. The grain sizes are selected by taking into account the diffusion length, $\boldsymbol{l_d = \sqrt{6DT}}$, to allow magnetization exchange between pores, where D is diffusion coefficient and T is the total time. The voxel in the numerical simulation has an edge length of 50 nm. The morphological models 1 and 2 have a grain radius of 150 and 450 nm, respectively. The porosities of these models are 8.5 and 15 p.u, respectively. Fig.1 displays a slice (cross-section) of the 2 layers model sample. The two morphological model structures were then used to create four samples of laminated sandstone of 2, 4, 6, and 8 layers of 300, 150, 100, and 75 voxel of thickness, respectively as seen in Fig. 2. Table 1 shows the variables used in the simulation model. Constant bulk-relaxation time T_{2b} of 3s was used for all simulation runs.

The simulation model uses a lattice random walk method to obtain T_2 relaxation time with CPMG sequence on a saturated porous system [8]. For better understanding the internal gradient, surface relaxivity, and layer thickness impact on diffusion coupling, series of tests has been conducted as follows:

- Across all models at different surface relaxivities of 2, 4, and 10 µm/s of RT-1 and constant 1 µm/s of RT-2.
- Across all models (4 different thicknesses) at grain susceptibilities of +5000 and -8 µSI of RT-1 and 2, respectively.
- Across 4-layers model at varied bulk susceptibility of -8, +1000, +2000 µSI for RT-1 and constant for RT-2 of -8 µSI. In this scenario, the T_2 distribution obtained for each morphological model structure along with the whole model.

A verification of signal-to-noise ratio was conducted by increasing the number of walker from 20,000 to 80,000 as seen in **Fig. 3**. This increase of S/N of a factor two results in a lowering of the automatically derived regularisation parameter and gives more emphasis to the physical relaxation time distribution. Seeing no change confirms that this distribution was already captured using 20,000 random walks.

3. Results

3.1 Surface Relaxivity Contrast vs. Layer Thickness

Surface relaxivity (ρ) effect has been tested across all model samples of the different layer thicknesses. The aim of this sensitivity is to test how much uncoupled pores signal will hold as bed thickness becomes smaller. **Fig. 4** shows that at Δρ of 1 µm/s (left), a bimodal T_2 distribution is formed with a minor degree of diffusion coupling. In addition, as the layer thickness decreases, diffusion coupling increases. Also, as Δρ decreases, the tendency to couple by diffusion increases. Thus, higher ρ leads to faster relaxing signal which will reduce pore coupling.

3.2 Susceptibility Contrast vs. Layer Thickness

Similar to the surface relaxivity sensitivity, bulk susceptibility (χ) contrast has been simulated on all layered samples. The aim was to test the impact of internal gradient contrast on diffusion coupling while varying the layer thickness. Internal gradients due to susceptibility contrast are calculated in the NMR simulator in the dipolar approximation [8]. RT-1 and RT-2 have χ of +5000 and -8 µSI, respectively. **Fig. 5** shows that as the layers thickness decreases, the degree of pore coupling increases and T_2 peaks of RT-2 (the larger pores) shifted to shorter times. Moreover, as layers become thinner, the high susceptibility minerals in one layer can greatly influence the NMR response of the offset layer. **Fig. 6** show a cross section of the internal gradient and magnetic field distribution of the 8 layer sample simulated.

3.3 Magnetization Breakdown

The aim of this section is to investigate the magnitude of diffusion coupling by comparing the NMR response of the laminated sample against the NMR responses of the individual rock types RT-1 and RT-2. The 4-layered sample has been utilized for this study by varying χ of RT-1 of [-8, +1000, +2000, +3000, +4000] µSI while keeping a constant χ of -8 µSI RT-2. The surface relaxivity was kept constant for both morphological models at 1 µm/s. The simulated NMR distribution for each morphological model was normalized by the total sample porosity. **Fig. 7** shows the response of three sets of NMR simulation runs.

4. Discussion and Conclusion

We observed the effect of diffusional coupling on transverse relaxation which may be qualitatively described by a relaxation time shift of T_2 distributions specific to morphological types. The effect is clearly more prominent with an increase of interlayer surface area enabling enhancing magnetisation exchange between distinctive environments at certain conditions. These conditions may be qualified with the aid of characteristic scales: $l_d >> l_s$ and $l_d >> l_g$, which may be effectively described by a strong localization regime, following notations of [3]. The observations above were made at fixed controlling parameters of NMR acquisition and subsequent inversion of acquired magnetisation decays (i.e. echo-spacing, number of echoes, SNR, inversion interval, number of eigenvalues and smoothing parameter). However, ILT which is used to invert the attained magnetization into T_2 distributions is known to be an ill-posed problem. The inversion involves a solution of a 1-st kind Fredholm integral with an exponential kernel [9]:

$$M(t) = \int_0^\infty f(T) \exp\left(-\frac{t}{T}\right) d\log(T)$$

where $M(t)$ is measured magnetisation, $f(T)$ is eigenfunction of spin density probability with eigenmodes f_n on preselected discrete log-spaced time scale T. The common condition imposed on a spectrum function is $f(T) \geq 0$. Noting a discrete nature of a problem and impose a smoothness as an additional constrain, the optimal solution may be expressed in the form of second norm minimization problem:

$$S(\alpha) = \sum_{j=1}^{m} [\int_0^\infty F(T) \exp\left(-\frac{t_j}{T}\right) dT - M(t_j)]^2 + \alpha \int_0^\infty F(T)^2 \, dT$$

where the solution is composed of non-negative functions F and $S(\alpha)$ is the residual as a function of the regularization parameter α. In this work the smoothing parameter is determined using L-curve method, Hansen (1992) [10], Arns et al. (2006) [11]. It is generally assumed that varying the smoothing parameter within an order of magnitude has no significant impact on the final distribution, Song et al. (2012) [12]. While with the constant (optimal) regularization parameter the merging of the originally well separated peaks is clear, for the purpose of rock-typing it might be meaningful to select less smoothly regularized solutions. We tested the approach by applying a 10 times smaller regularization parameter to invert NMR signal which we interpreted as subjected to strong diffusional coupling. In one instance the effect was achieved using surface relaxivity contrast between morphological types and in another by difference in susceptibility induced field gradients as seen in **Fig. 8** and **Fig. 9**.

We observed and demonstrated on **Fig. 8** and **Fig. 9** the effect of sharpening ILT solutions with regularization parameter which seemingly reverses back the original coupling effect. The peak positions of the two populations are very similar for the layered system as seen in Fig. 8 and Fig. 9. However, the relative fractions of the two rock-types should be equal and are not recovered, in particular for the 8-layered case. We conclude that diffusion coupling is visible when using the optimal regularisation parameter. In terms of rock-typing finding the initial rock-classes should be feasible, if they are independently measured beforehand and the effect of diffusion coupling on the relative peak-weighting is understood.

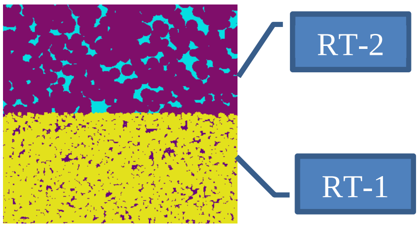

Fig. 1: 2D slices through the 2-layered model to represent the laminated sandstone. Rock type 1 (RT-1) has grains of diameter d=900 nm and a porosity of ϕ=8.5%, and RT-2 has d=300nm and ϕ=15%.

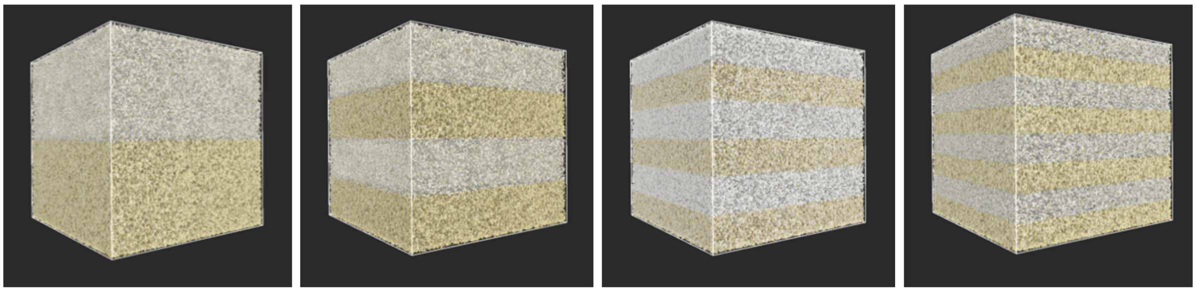

Fig. 2: 3D images of the constructed 2-, 4-, 6-, and 8-layer laminated sandstone models.

Table 1- NMR simulation model parameters.

Sample size [voxel^3]	Static Magnetic Field [Gauss]	No. of Random Walkers (RW)	Echo Spacing (T_E) [μs]	Hydrogen Index	Diffusion Coefficient (D) [μm^2/s]	Fluid Bulk Susceptibility [μSI]
600^3	470	20,000	100	0.94	2,300	-10

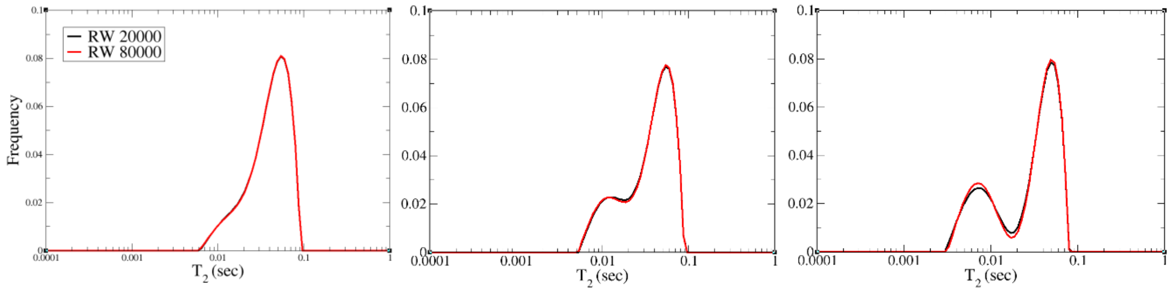

Fig. 3: Sensitivity study comparing calculations using 20,000 random walks (RW) against 80,000 RW for a 4-layered model. From left to right bulk susceptibilities of RT-1 were [-8, +1000, +2000] μSI and constant of [-8] μSI of RT-2.

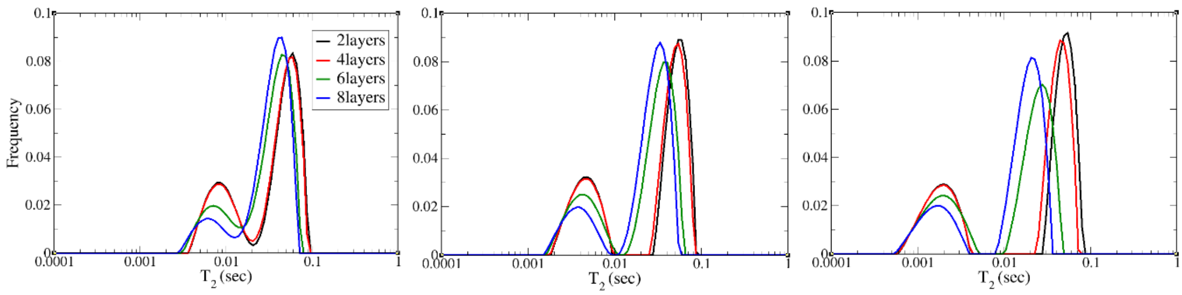

Fig. 4: NMR relaxation time distribution for 4 different thicknesses at $\Delta\rho$ of [1, 3, 9] μm/s from left to right. Constant susceptibility of -8 μSI for both rock-types was applied.

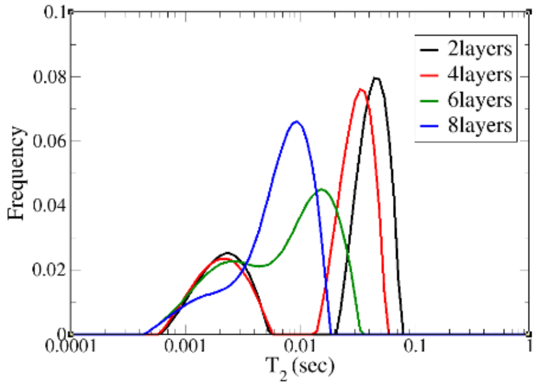

Fig. 5: NMR relaxation time distribution for 4 different thicknesses of [+5000, -8] µSI grain susceptibility of RT-1 and RT-2, respectively and constant surface relaxivity.

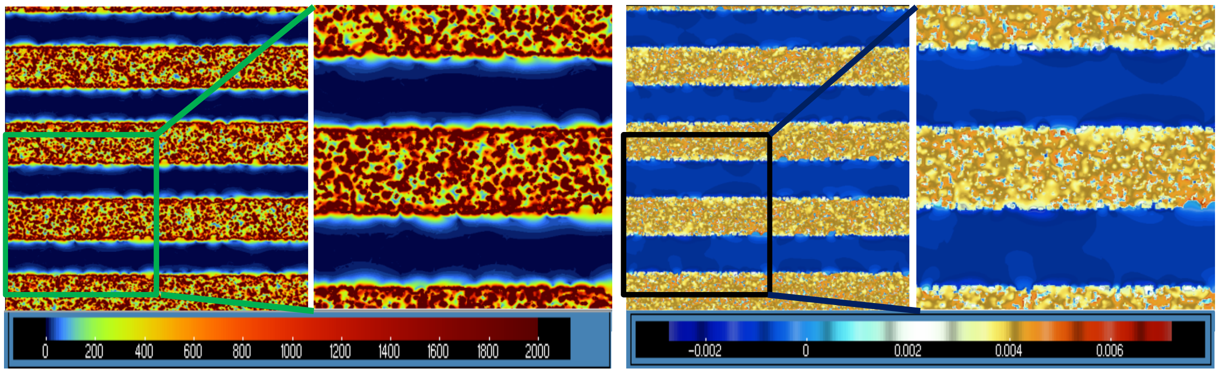

Fig. 6: 2D slices through the internal gradient field (left) and the magnetic field distribution (right) for the 8 layer sample at constant surface relaxivity. The units are in B0/cm for the gradient fields and in units of B0 for the magnetic field. The range of the internal gradients was truncated at 2,000 to make the weaker longer range gradients visible.

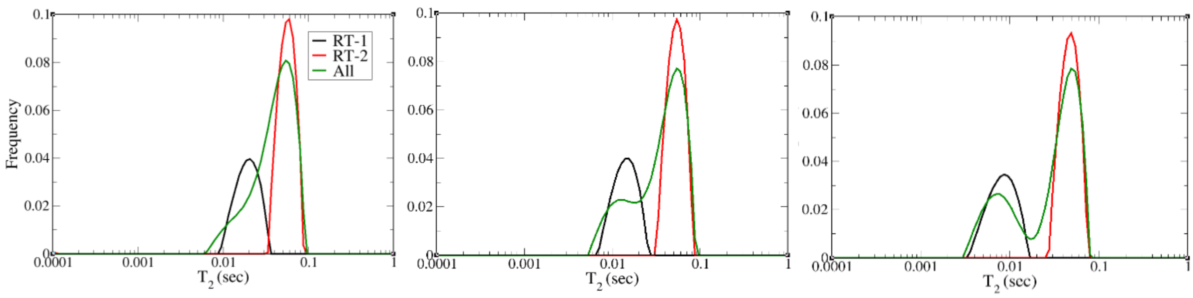

Fig. 7: NMR distribution of each morphological model structure within 4-layer sample along with whole sample response. From left to right, χ [-8, +1000, +2000] µSI for RT-1 and constant χ [-8] µSI for RT-2

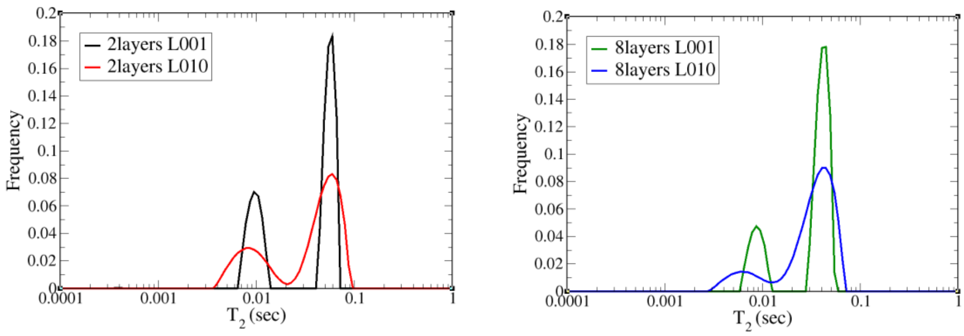

Fig. 8 T_2 distributions of 2- (left) and 8-layers (right) model structures represented by equal fractions of two morphological types with 1 µm/s relaxivity contrast between them and equal bulk susceptibility of -8 µSI.

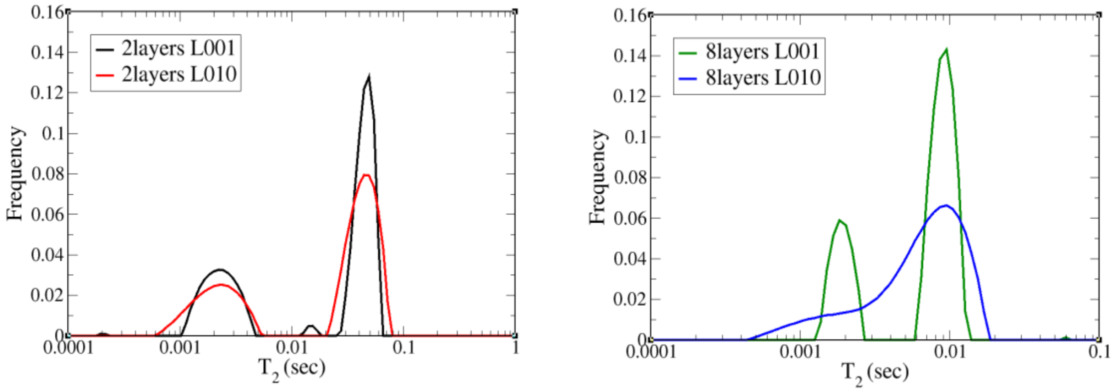

Fig. 9 T_2 distributions of 2- (left) and 8-layers (right) model structures where two types of morphologies are similar in surface relaxivity of 1 µm/s, but have assigned a high difference in fluid-solid susceptibility

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