A COMPARATIVE STUDY OF RESERVOIR PORE STRUCTURE BY 2D AND 3D IMAGE ANALYSIS, MERCURY POROSIMETRY AND NMR RELAXOMETRY

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Interpretation of NMR transverse relaxation measurements in terms of T_2 distributions underlies the estimation of petrophysical properties (Kenyon, 1997), including the porosity, clay bound water, pore size distribution, saturation, permeability and capillary pressure. Uncertainties associated with the scaling between T_2 and pore size contribute to the difficulty of NMR-based petrophysical interpretations, as are uncertainties related to the proper choice of NMR test parameters (e.g., inter-echo spacing) and uncertainties associated with multi-exponential decomposition. Some of these issues were explored in this study using complementary information from mercury porosimetry, backscatter SEM image analysis and 3D reconstruction and characterization. Complete results from fused and packed glass bead, sandstone and dolomite samples will be presented in the poster. Representative results are reported here.

Monitoring of the time-dependent proton magnetization $M_{xy}(t)$ using the CPMG pulse sequence was carried out at $S_w = 1$ and $S_w = S_{wr}$, the latter condition established by centrifugation or, in the case of a glass bead packing, by gravity drainage. NMR relaxation tests were performed at 0.6 Tesla using a modified Bruker SXP 60 Pulse NMR spectrometer at 26.6 MHz and repeated on a Corespec-1000. Two different multi-exponential analysis methods were compared, non-negative least squares (NNLS) and a simulated annealing algorithm (SA) developed in house. Multi-exponential analysis yielded an interpretation of the decay of transverse magnetization in terms of a discrete distribution of relaxation times:

$$M_{xy}(t) = \sum_{i=1}^{n} M_{0i}\, exp\left[-\frac{t}{T_{2i}}\right] \tag{1}$$

Alternatively, a compact interpretation was obtained by fitting the magnetization data to the modified stretched exponential (MSE) model (Peyron *et al.*, 1996):

$$M_{xy}(t) = M_0\, exp\left[-\frac{t}{T_o}\left(1+\frac{t}{T_c}\right)^{\beta-1}\right] \tag{2}$$

Fitting of the magnetization decay data with the MSE model provided the initial spin-relaxation rate $1/T_0 = \rho(S/V_p)$, where ρ is the surface relaxation strength and S/V_p is the average pore surface to pore volume ratio. Additionally, the long-time limit constant of the diffusion and relaxation processes was given by $T_D = T_0^{1/\beta}(T_c)^{(\beta-1)/\beta}$.

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Typical backscatter SEM images of the microstructure of different samples are shown in Figure 1. Each binary image is a discrete map of the phase function, $Z(\vec{r})$, which takes the value of unity if $\vec{r}$ points to pore space and the value of zero otherwise. Essential morphological parameters, including the porosity, f, and the pore space autocorrelation function, $R_z(u)$, were computed from the image data (Ioannidis *et al.*, 1996). The specific surface area ($s = S/V$) was obtained from $R_z(u)$ as:

$$s = -6(\phi - \phi^2)\left.\frac{dR_z}{du}\right|_{u=0} \tag{3}$$

The autocorrelation functions of the samples shown in Figure 1 are depicted in Figure 2. Table 1 lists some of the statistical and NMR properties of these samples. For the glass bead samples, in which microporosity is absent, image analysis provides accurate estimates of s from which the surface relaxivity r can be obtained if T_0 is also known. For three different fused bead samples we have obtained $r = 100 \pm 17$ μm/s. This value is greater than the one reported by Kleinberg (1996).

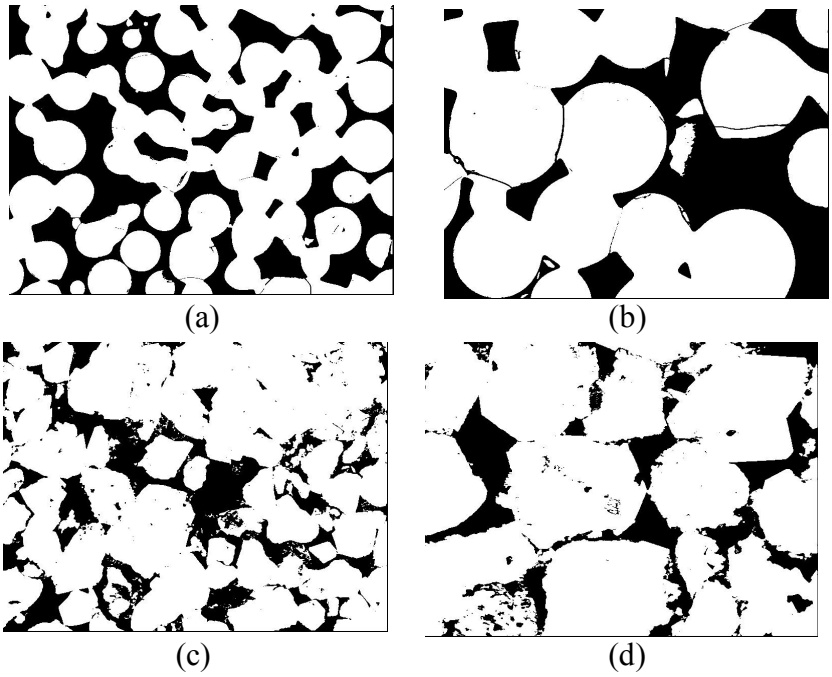

Figure 1. Typical binary backscatter SEM images (765x573 pixels; image resolution listed in Table 1). (a) Glass bead sample GB1, (b) Glass bead sample GB2, (c) Berea sandstone sample, (d) Moomba sandstone sample.

Table 1: Image statistical information and characteristic transverse relaxation times.

	ϕ (fraction)	s (μm^{-1})	Resolution (μm/pixel)	Correlation length (μm)	T_0 (s)	T_D (s)
Berea	0.202	0.0575	1.55	27.7	-	-
GB1	0.335	0.0318	2.09	33.7	0.125	0.163
GB2	0.380	0.0156	2.09	80.2	0.210	0.286
Moomba	0.203	0.0447	1.55	37.7	-	-

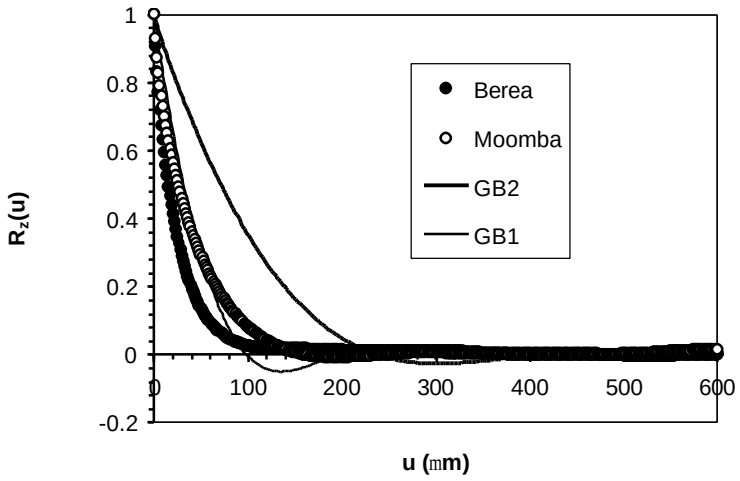

Figure 2. Autocorrelation functions of the samples listed in Table 1.

Average pore radii determined from T_D using this value of r agree well with the measured correlation lengths (Table 1). A higher value of r is also consistent with observations made using a packing of monosized beads ($D_p = 250$ μm) (Figure 3).

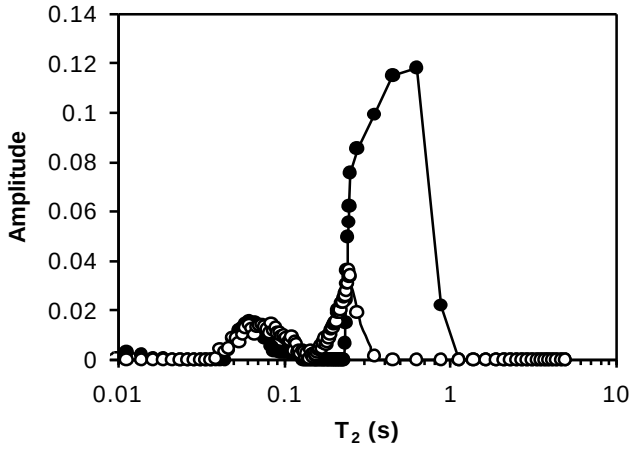

Figure 3. T_2 distributions in bead pack. Solid circles: $S_w = 1$ ($T_0 = 0.12$ s, $T_D = 0.27$ s); empty circles: after gravity drainage, $S_w = 0.1$ ($P_c = 38$ kPa, $T_0 = 0.11$ s, $T_D = 0.12$ s).

Good agreement between NMR and SEM porosity was found in all cases, provided that M_0 was accurately determined. T_2 distributions obtained by different multi-exponential decomposition methods and different equipment were also in good agreement, provided that a sufficiently small echo spacing was used (see Figure 4). NMR relaxation in a 3D stochastic replica of Berea sandstone was modeled using a random-walk algorithm and compared to the predictions of Eq. (1) using the pore size distribution obtained by 3D pore space partitioning (Liang *et al.*, 2000). Fig. 5 shows general agreement but also some differences, which may be attributed to diffusional averaging.

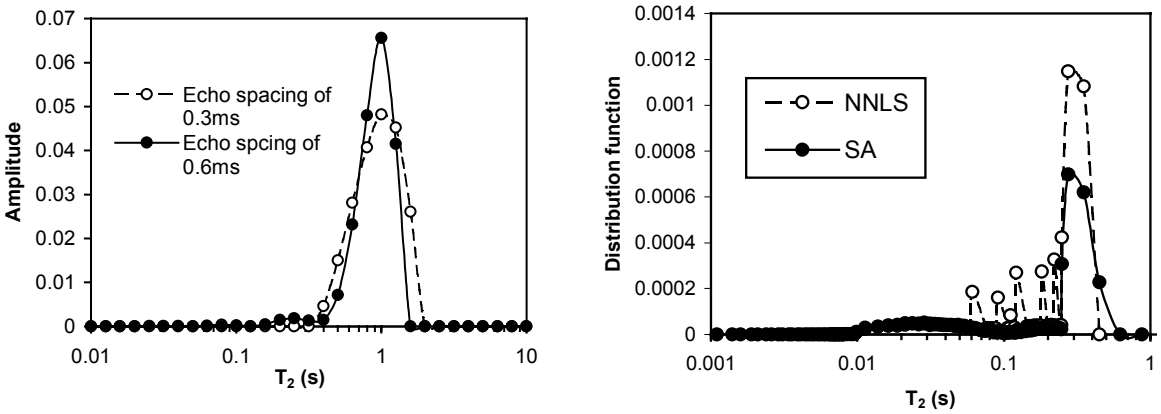

Figure 4. Left panel: Effect of echo spacing on T_2 distribution (GB1 sample, $S_w = 1$, NNLS inversion). Right panel: Effect of inversion method on T_2 distribution (Berea sample, $S_w = 1$, echo spacing of 0.5 ms).

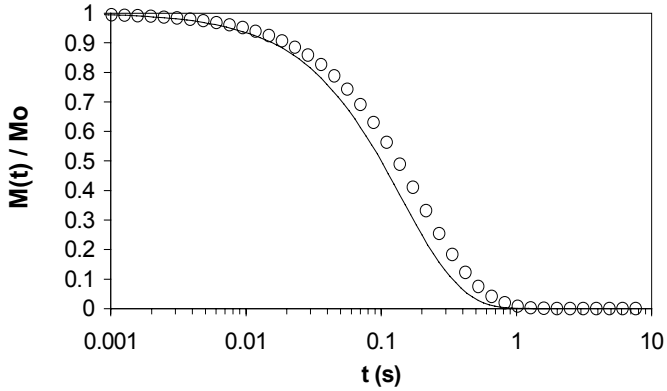

Figure 5. Magnetization decay in 3D stochastic replica of Berea sandstone ($\rho = 12.8$ μm/s). Points: Eq.(1), line: random-walk simulation.

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