AN EVALUATION OF THE APPLICATION OF LOW FIELD NMR IN THE CHARACTERIZATION OF CARBONATE RESERVOIRS

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ABSTRACT

Low field Nuclear Magnetic Resonance (NMR) as an analysis tool for reservoir studies is a relatively new and promising technology that is fast, nondestructive and able to yield a vast amount of information about the reservoir formation. In theory, a single NMR measurement can be used to determine porosity, permeability, and irreducible water saturation. Much of the earlier work with NMR was performed on sands or sandstones. When these models were applied to carbonates, the rock properties predicted were very different from those measured through core analysis, and were often incorrect. Thus the conventional method of interpreting NMR data needs to be changed to accommodate the difference between sandstones and carbonates. This paper details an investigation of the bound and free fluid components of carbonates through the use of NMR and Computed Tomography (CT) analysis. Such information is required for estimates of pore connectivity and recoverable reserves.

NMR $T_{2cutoff}$ values vary in carbonates. Correlations were observed between $T_{2cutoff}$ and the fully saturated NMR spectrum. These correlations could be used on a logging tool as a rough estimate of moveable fluid volume in different zones. $T_{2cutoff}$ was also observed to correlate well with the NMR spectrum at S_{wi}, which represents the pores that are not drained. In this manner, NMR $T_{2cutoff}$ values are thought to be indicative of the connectivity of the pores. To test this hypothesis, CT data were obtained and visually compared to the NMR data in order to confirm the relationship between NMR $T_{2cutoff}$ and pore connectivity. This verifies that NMR $T_{2cutoff}$ analysis for estimates of moveable fluid volumes can be used to provide information about pore connectivity in carbonates.

INTRODUCTION

Conventional reservoir studies consist of core and/or log analysis which can be time consuming and expensive. NMR is an alternative technology that is fast, nondestructive and able to yield a vast amount of information about the reservoir formation[1]. In theory, a single NMR measurement can be used to determine porosity, permeability, and irreducible water saturation. Most of the earlier work for NMR was performed on sands or sandstones[1,2,3]. From this data, correlations between NMR parameters and rock characterization were developed with results that were comparable to conventional core analysis. However, when the same models and correlations were applied to carbonates, the rock properties predicted were very different from those predicted by core analysis,

and were often incorrect[4]. Thus the conventional method of interpreting NMR data needs to be changed to accommodate the difference between sandstones and carbonates.

Sandstones are usually well sorted and tend to have a more uniform pore size distribution, meaning that the pore throat distribution is uniform as well. Carbonate porosity, on the other hand, includes intercrystalline spaces, which are usually tight, and vugs that vary in size. The presence of vugs will increase the total porosity, but this does not mean that the fluids inside the vugs will be produced. The processes of leaching of the grains in carbonates control the ability of the vugs to be connected and drained. Dissolution around the original pores will enlarge the pores and throats and will help the draining process by improving connectivity. However, moldic vugular porosity, which is formed by a selective removal of specific grains in the rock[5], might increase the pore size but not the throat size. This process may instead decrease the overall connectivity. In yet another process where vugs are formed by cutting across the grains, connectivity may increase or decrease.

The complicated pore structures of carbonates have prompted an investigation in this paper of the bound and free fluid components of carbonates through the use of NMR and CT analysis. The NMR spectra obtained, which provides information on pore size distribution, can potentially be used to extract the connectivity information of the pores. CT is used to help visualize the different pore systems in carbonates, and verify the findings made with NMR.

THEORY

NMR measures the ability of hydrogen protons in a porous medium to relax after being subjected to a magnetic field sequence. The T_2 spectra obtained from NMR are proportional to a pore size distribution. Thus a $T_{2cutoff}$ value can be employed to separate the bound (small pores) and moveable (larger pores) fluids. A more detailed explanation of NMR theory is given by Coates *et al.*[6].

Relaxation Mechanisms

The hydrogen protons existing in the pores relax through three different mechanisms: bulk fluid, surface, and diffusion in the presence of magnetic field gradients[6].

Bulk relaxation is a property of the fluid and is caused by local diffusion of the fluid molecules; the protons relax as energy is transferred to other molecules. This relaxation is essentially the same as the relaxation of the same fluids in a large container. Bulk processes are controlled by the physical properties of the fluid, such as viscosity and chemical composition, and by external conditions such as temperature and pressure. Diffusion relaxation occurs when a significant gradient exists in the magnetic field. As the protons diffuse through this gradient, they de-phase and the magnetic signal is lost, which appears as additional relaxation.

An important relaxation mechanism for water in porous media is surface relaxation. This occurs at the fluid-solid interface where the hydrogen protons approach the grain surfaces and transfer energy to the walls.

$$\frac{1}{T_{2s}} = \rho\left(\frac{S}{V}\right) \quad (1)$$

Where $T_{2s} = T_2$ relaxation time resulting from surface interactions
ρ = surface relaxivity
(S/V) = surface to volume ratio

This implies that protons in smaller pores relax faster than protons in larger pores since smaller pores have a higher surface to volume ratio, which enhances surface relaxation rate ($1/T_{2s}$). Surface relaxivity differs with rock type; carbonate surfaces tend to have weaker surface relaxivity than quartz[6]. This mechanism of relaxation is independent of temperature and pressure.

T_2 Distribution

In the absence of an external magnetic field gradient, diffusion relaxation is insignificant. Surface and bulk relaxation are therefore the main relaxation mechanisms of hydrogen protons in porous media detected by low field NMR. Hydrogen protons of water existing near the surface relax much faster than bulk water, since surface relaxation is a function of the surface to volume ratio of the pores. This means that when the porous medium is fully saturated with water, the NMR decay can be inverted into a T_2 spectrum, which is analogous to the pore size distribution of the porous medium.

It is commonly assumed that the fluids in small pores will not be produced and the fluids in the larger pores will be produced. A fixed value of T_2, known as a $T_{2cutoff}$, can therefore be used to separate these bound and free fluid portions. In the literature, it was reported that the cutoff value for sandstones is about 33 ms and for carbonates, the common value of 100 ms is used as a cutoff for bound water[1,3,7,8]. The bound region with $T_2 < T_{2cutoff}$ corresponds to small pores that were not produced, and also the remaining water film in larger pores. It is widely accepted that $T_{2cutoff}$ values vary with lithology, as seen in complex sandstones and especially in carbonates, where rock properties vary significantly. There are also other parameters that affect this cutoff value as well, such as the pore body diameter to pore throat diameter (the aspect ratio). In formations where the aspect ratio is large, it is expected that there is a larger percentage of trapping compared to a smaller aspect ratio. Currently, all the variables that affect $T_{2cutoff}$ are not fully identified nor understood.

Computerized Tomography

CT (or CAT) technology is an established tool that can be used to aid in reservoir characterization. The main principle behind CT is that it uses an X-ray source that rotates

around the sample to obtain one-dimensional projections of x-ray attenuation at different angles[9]. From this data, the cross-sectional slice of the sample can be reconstructed. The resolution is about 0.5 x 0.5 mm while the slice thickness can vary from 1 mm to 15 mm. The CT produces 2-D arrays of CT numbers that can be translated to density and then to voxel porosity using[10]:

$$\phi = \frac{\rho_g - \rho_b}{\rho_g - \rho_f} \tag{2}$$

Where ρ_g = grain density
ρ_b = bulk density
ρ_f = fluid density
ϕ = voxel porosity

PROCEDURE

A large set of carbonate samples was collected from various fields in Western Canada. This data set consists of about 80 samples, from six different formations.

Conventional core analysis measurements were used along with NMR to provide comparisons for the results obtained from NMR data. Gas expansion was performed on the dry plugs at an overburden pressure of 300 psi. The cores were then vacuum saturated with brine and placed in the NMR to obtain spectra at fully saturated conditions. The cores were then centrifuged in air at a speed of 6000 rpm, which corresponds to a capillary pressure of approximately 200 psi, for 6 hours at 30°C. The cores were then weighed and NMR spectra at the irreducible condition were collected. The NMR spectra were obtained using a Corespec 1000™ relaxometer at a frequency of 1 MHz at a time echo of 0.3 ms with 5000 echoes. The cores were also CAT-scanned at dry, fully saturated, and irreducible conditions using a GE9800 with 140 kV and 70 mA, with slices taken every 3 mm.

RESULTS

Porosity estimates from the different samples are compared below, along with a detailed investigation of $T_{2cutoff}$ using NMR data and CT data.

Porosity

The porosity of each plug was found using four different methods: gas expansion, NMR, CT analysis of wet cores, and CT analysis of dry cores. The comparison between NMR porosity and gas expansion yields a slope of 1.09 and an R^2 fit of 0.92[11] while the comparison between gas expansion and porosity obtained from CT data at fully saturated condition gives a slope of 0.99 and a fit of 0.89[12]. The porosity of the core can be obtained from the CT data at the dry condition and fully saturated condition by using equation (2). The comparison between these porosities is shown in Figure 1.

Figure 1 contains fewer points than in the fully saturated plots[11,12] due to the fact that the carbonates cores were very fragile. By the time the cores were prepared for CAT-scanning at the dry condition, many of them had been chipped or broken so only the undamaged original cores were scanned. Many of the cores had been altered slightly before they were scanned dry, which explains the difference between the two CT porosity estimates. However, the agreement between the two sets of CT data is still satisfactory.

In Figure 2 the porosity obtained from CT data at the dry condition is compared to the porosity values obtained from gas expansion. Again, the agreement is very good. Figures 1 and 2 provide assurance that the CT information gathered does accurately capture the porous spaces in the samples, so CT data can be used to aid the NMR.

$T_{2cutoff}$ from NMR Data

The spectra of a sample at fully saturated and irreducible water saturations are shown in Figure 3. The difference between the spectra corresponds to the brine that was drained. The figure also shows that at low T_2, which corresponds to brine in the small pores, there was no production of brine. At large T_2, which corresponds to brine in the large pores, a significant amount was drained. $T_{2cutoff}$ values are found by comparing the cumulative amplitude of both spectra, as shown in Figure 4. $T_{2cutoff}$ is the value at which the cumulative amplitude in the fully saturated NMR spectra equals the total amplitude of the spectra at S_{wi} condition.

The $T_{2cutoff}$ values for this data set were reported previously[11] and were seen to range from around 10 to 1000 ms. One concern was that at the end of the spinning process, end effects might be present. The CT data at three different conditions (dry, saturated and with irreducible water) were used to check the CT number at S_{wi} along every slice. Some of the data did show end effects, so these cores were removed from the correlation. As it happens, some of the cores with end effects also have high $T_{2cutoff}$ values.

It was seen that the size and the location of the peaks in the NMR spectra are not always the same, which is a reflection of differences in pore structure for the different samples. Thus, the $T_{2cutoff}$ values are compared with the geometric mean of the fully saturated spectra in Figure 5. The geometric mean,T_{2gm}, is defined as:

$$T_{2gm} = \exp\left[\sum_{Ts}^{T_{2max}} \frac{A_i}{A_T} \ln(T_{2i})\right] \qquad (3)$$

Where T_{2max} =10000 ms
A_i = amplitude at T_{2i}
A_T = total amplitude of the NMR spectrum
T_{2s} = T_2 at which the spectrum begins
T_{2i} = the individual values of T_2

It was seen that as the geometric mean of the spectra increases, the $T_{2cutoff}$ value increases. The increase in geometric mean implies that the T_2 distribution is wider as the porous media has a broader range of pore sizes. This wider range of pore sizes leads to a higher $T_{2cutoff}$.

A better relationship is seen when $T_{2cutoff}$ is plotted against the size of the last peak in Figure 6. The size of the last peak is the summation of the NMR amplitudes making up this peak that occurs close to 1000 ms, expressed as a fraction of the total amplitude. The trend in the figure shows that as the relative size of the last peak increases, the $T_{2cutoff}$ value decreases. A larger last peak means that the sample has a greater percentage of large pores. More of these large pores will be drained, making $T_{2cutoff}$ small. It should be noted that it is not always easy to correctly determine the size of the last peak due to overlapping with other peaks at occur at smaller T_2 values, as shown in Figure 7. This is responsible for some of the scatter in the data of Figure 6. An attempt is currently being made to de-convolute the peaks to obtain a better fit.

$T_{2cutoff}$ is also compared to the geometric mean of the last peak to yield a nonlinear relationship between them, as shown in Figure 8. This figure shows that as the geometric mean of the last peak increases, meaning that the peaks shifts further to the right, the $T_{2cutoff}$ value increases. As the spectra shifts toward the right, this implies that the pore distribution is wider and the difference between the small and large pores is more significant. This could mean that the aspect ratio is higher, thus more trapping occurs which leads to higher $T_{2cutoff}$. This relationship is similar to that of Figure 6, but the trend seen in Figure 8 is better. Due to the overlapping of the peaks, the calculated geometric mean of the last peak might create some of the scattering seen in the figure. Samples that contain significant large pores that are well connected contribute to further scattering. The correlation seen in Figure 8 is not highly accurate, but it could be potentially used on an NMR logging tool to identify rough moveable fluid estimates in different zones.

Figure 9 compares $T_{2cutoff}$ with the relative size of the last peak in the NMR spectra at S_{wi}. Again, a nonlinear relationship is seen. This relationship also shows that as the size of the last peak in the NMR spectra at S_{wi} increases, $T_{2cutoff}$ has to increase to accommodate the increase in trapping of the large pores. This figure identifies a relationship between fully saturated cores and cores at S_{wi}. Finding the $T_{2cutoff}$ from either condition provides information about the other condition.

CT Data Analysis

As mentioned before, connectivity is a major factor that controls the drainage of the pore and hence the $T_{2cutoff}$ values. Various samples with low, moderate and high $T_{2cutoff}$ values were chosen to illustrate the nature of the porous medium. The visual images obtained using CT can be used as verification of the $T_{2cutoff}$ values calculated from NMR.

Figure 10 shows two cores that have very low $T_{2cutoff}$ values, indicating good drainage of the pores. The slice number is increasing from left to right and down the rows. The core

on the left has 14 slices with uniform large pore space, as indicated by the smooth light color. This core has a porosity of 0.17 and a permeability of 17 mD. The core on the right has 13 slices with vugs that are well connected and a lower matrix porosity (darker shade). The evidence of good vug connectivity is seen as the slices all show large vugs in the upper half of the core. Overall, the porosity of this core is about 0.11 and the permeability is 105 mD.

The core in Figure 11 has 9 slices with a porosity of 0.12 and a permeability of 88 mD. It has many small regions of high porosity (dark color), which may not all be drained, since the high porosity area are not in the same location in all the slices. This means that only some of the vugs are connected, so $T_{2cutoff}$ is higher than the samples in Figure 10.

The core on the left of Figure 12 shows a tight porous medium (dark color) with a few isolated vugs (dark regions). This core has a porosity of 0.11 and a permeability of 0.45 mD. The sample on the right shows more vugs that do not seem to be connected (location of the vugs changed with slices). This sample has a porosity of 0.085 and a permeability of 0.7 mD. Both of these cores have high $T_{2cutoff}$ values, meaning that there will be more trapping in these cores.

CONCLUSIONS

One of the most important pieces of information to be gained from core analysis of carbonates is the bound and moveable fluid volumes. NMR $T_{2cutoff}$ analysis is used to separate these different fluid regions, which gives an estimate of recoverable reserves and pore connectivity.

NMR, CT and gas expansion all yield similar estimates of porosity in carbonates. This provides assurance that NMR and CT are both capable of capturing the entire porous medium of the measured samples.

NMR $T_{2cutoff}$ values are not fixed in carbonates. The T_{2gm} of the NMR spectrum is a measure of the variation in pore size in that sample. A correlation was observed between $T_{2cutoff}$ and the T_{2gm} of the saturated spectrum. A correlation was also seen with $T_{2cutoff}$ and the T_{2gm} of the last peak of the spectrum, which represents the large pores and vugs. This correlation could be used on a logging tool as a rough estimate of moveable fluid volume in different zones.

$T_{2cutoff}$ was also observed to correlate well with the relative fraction of the last peak of the NMR spectrum at S_{wi}, which represents the large pores that are not drained. In this manner, NMR $T_{2cutoff}$ values are thought to be indicative of the connectivity of the pores in a carbonate core. To test this hypothesis, CT data were obtained and visually compared to the NMR data. Samples that had low $T_{2cutoff}$ values ($T_{2cutoff} < 100$ ms), indicating good drainage, had high intercrystalline porosity or good connectivity of vugs. On the other hand, samples that had high $T_{2cutoff}$ values ($T_{2cutoff} > 100$ ms) showed low

matrix porosity and poor vug connectivity. In this manner, CT analysis confirmed visually the relationship between NMR $T_{2cutoff}$ and pore connectivity.

NMR has been shown to provide pore size distributions even for carbonate rocks. Using $T_{2cutoff}$ analysis for estimates of moveable fluid volumes, NMR can be used to provide information about pore connectivity in carbonates as well.

ACKNOWLEDGEMENTS

The authors wish to thank Michael Benedek of TIPM for CAT-scanning all the cores, and Natalia Mirotchnik of TIPM for performing some of the NMR measurements. They also wish to thank the numerous donors of carbonate samples. The financial support provided by NSERC, COURSE and Suncor Inc. is greatly appreciated.

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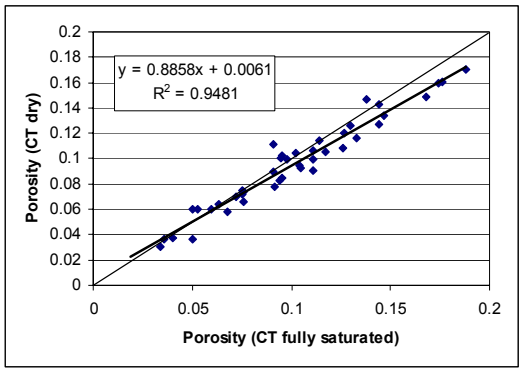

Figure 1. Porosity obtained from CT data

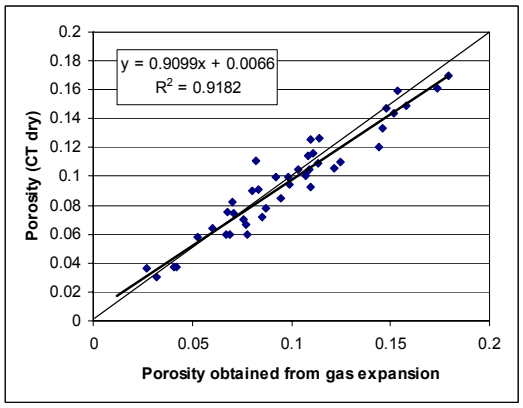

Figure 2. Porosity comparisons

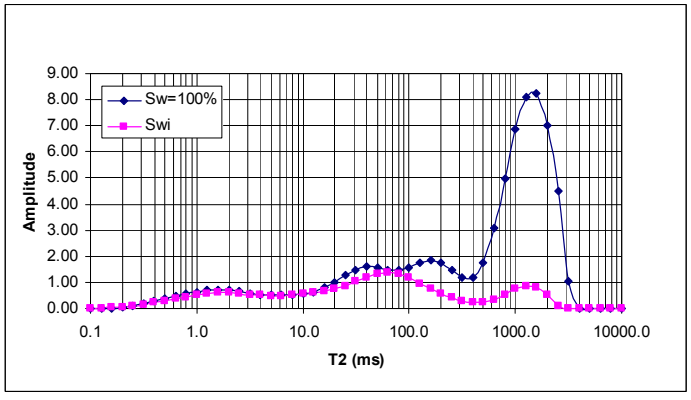

Figure 3. NMR spectra at fully saturated and S_{wi}

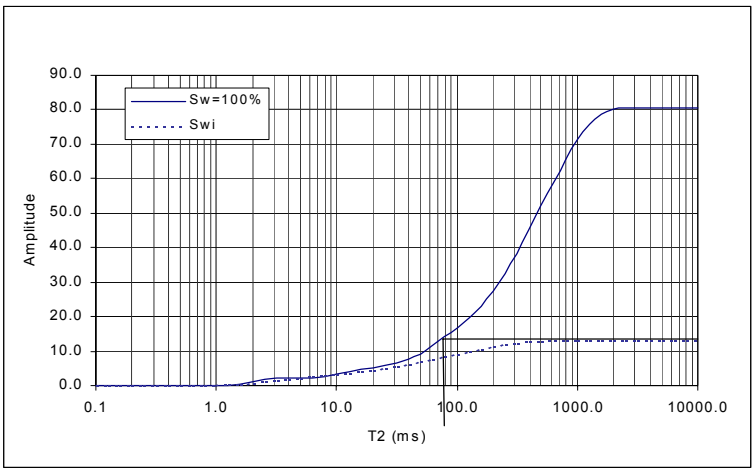

Figure 4. $T_{2cutoff}$ determination

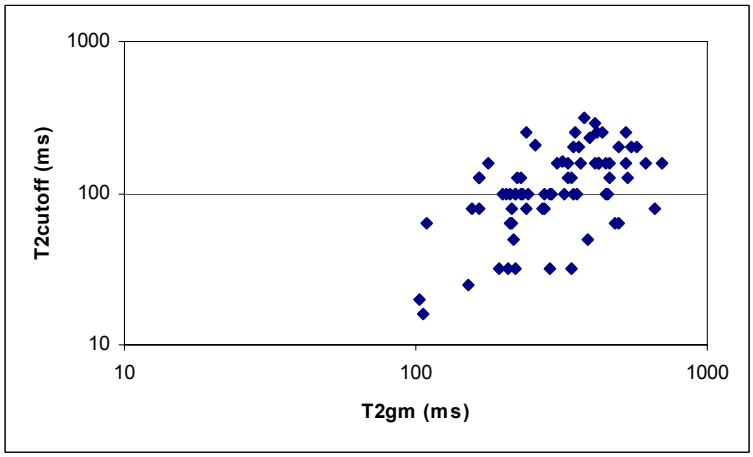

Figure 5. $T_{2cutoff}$ vs T_{2gm} of fully saturated samples

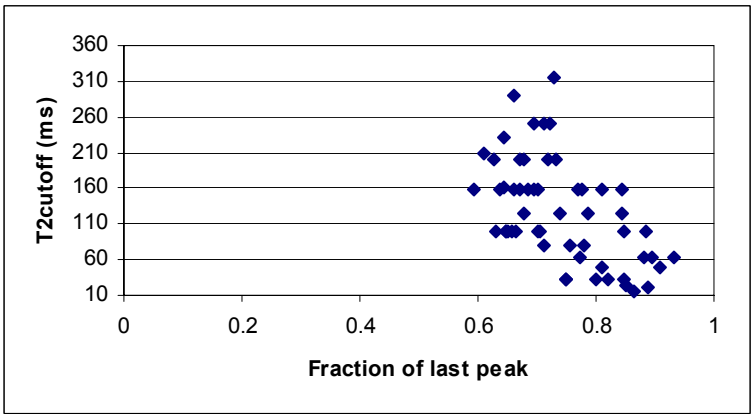

Figure 6. $T_{2cutoff}$ vs last peak as a fraction of the total amplitude

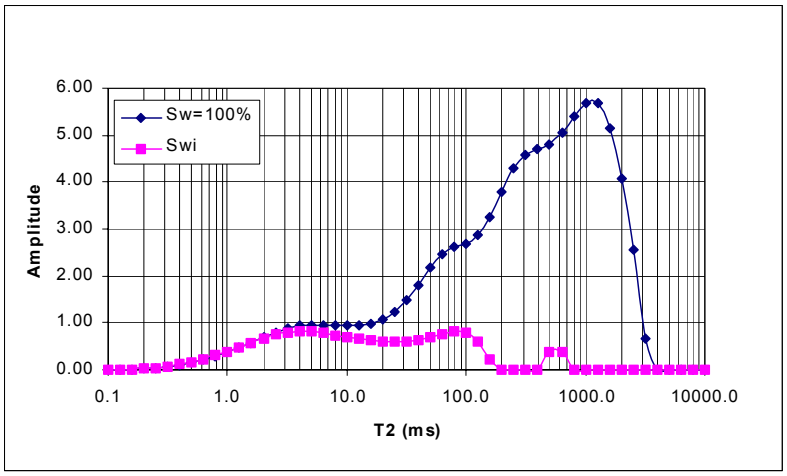

Figure 7. Overlapping of peaks

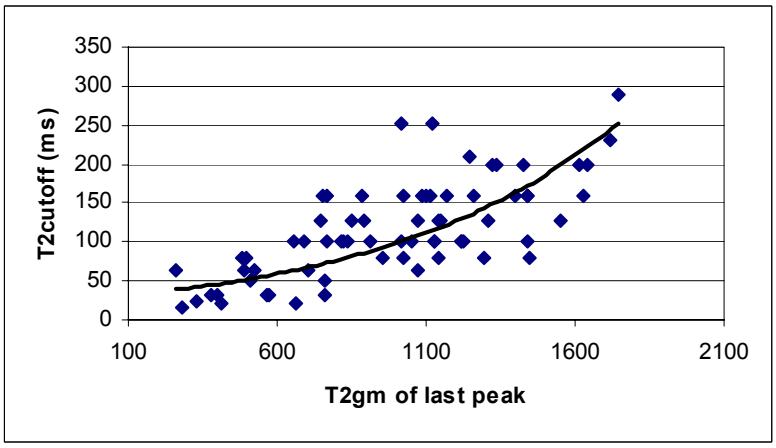

Figure 8. $T_{2cutoff}$ vs T_{2gm} of last peak of saturated spectrum

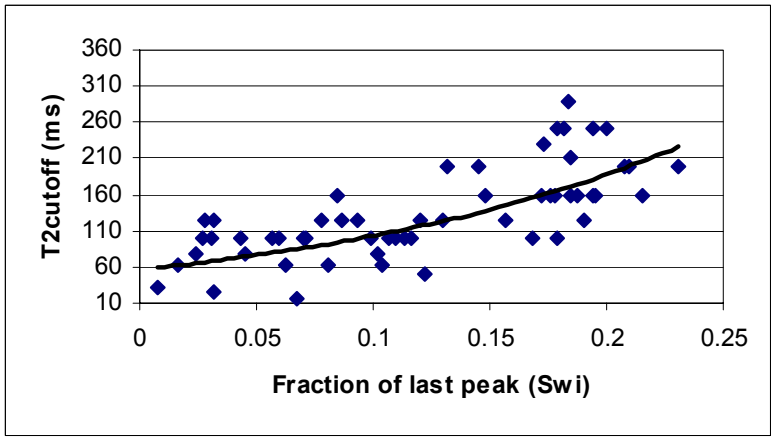

Figure 9. $T_{2cutoff}$ vs last peak as a fraction of total amplitude of S_{wi} spectra

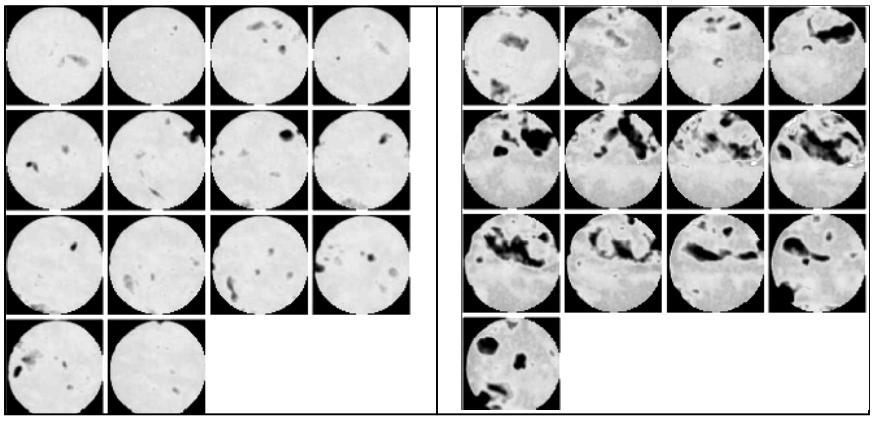

Figure 10. Samples with low $T_{2cutoff}$ values

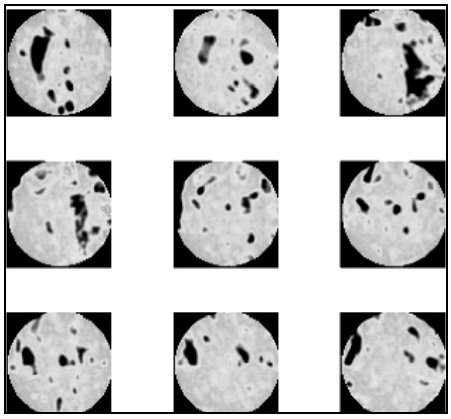

Figure 11. Sample with moderate $T_{2cutoff}$ value

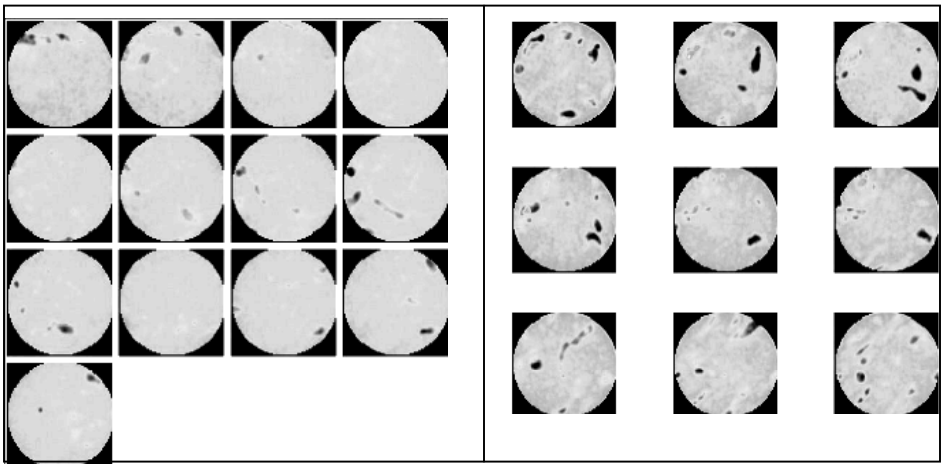

Figure 12. Samples with high $T_{2cutoff}$ values