STUDY OF NMR POROSITY FOR TERRESTRIAL FORMATION IN CHINA

Wang Xiaowen Xiao Lizhi Xie Ranhong and Zhang Yuanzhong

(China University of Petroleum, Beijing China)

This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Toronto, Canada, 21-25 August 2005

Abstract

NMR logging is an effective method for porosity measurement because the log response only comes from the pore fluid and is, in principle, not affected by rock matrix. However, it is found that porosity difference between NMR and core porosity logging is unacceptable in terrestrial formation in China, sometimes as big as 2 to 6 pu.

We analyzed the cause of the porosity difference based on laboratory NMR core measurements using the same parameters for data acquisition and processing as those for Halliburton's MRIL logging. More than 40 samples with a wide range of porosities including sandstones and artificial ceramic were chosen for the core and NMR porosity measurements. When using the current data acquisition parameters and processing method, the differences between the core and NMR porosities for the artificial ceramic and Berea sandstones were less than 1 pu and are considered acceptable, whereas those for the terrestrial sediment sandstones were very big. Through repeated trials, a new method is put forth, having a long wait time TW_L 5s and a long echo spacing TE_L=0.9ms for effective porosity, and a short wait time TW_S 10ms and a short echo spacing TE_S=0.3ms for bound water porosity. Using this method, the differences between the core and NMR porosities for the terrestrial sediments become reduced and acceptable. It is suggested that appropriate data acquisition and processing method should be determined according to the formations to obtain accurate NMR porosity.

Introduction

Since 1927, a set of well logging technologies for determining total porosity has come into being, such as neutron, density, and sonic, etc. These conventional porosity logging methods can obtain accurate porosity values when the geology is simple and lithology, matrix components are uniform. However, for complex reservoirs, especially for the low-porosity and low-permeability reservoirs, these conventional porosity logging methods are much less accurate. They are more sensitive to matrix materials than to pore fluids. The responses of these tools are highly affected by the borehole condition,

mudcake, and the complexity of the matrix components, and the sensitive volumes of these tools are not very well defined [1]. The accuracy of the response equation, the reliability of model parameters, and the match of vertical and radial resolutions can all affect the interpretation result, leading to errors in porosity determination.

Nuclear magnetic resonance (NMR) logging response is, in principle, not affected by matrix component, and is sensitive to fluid properties only. We have used Halliburton's MRIL log to differentiate clay-bound water, capillary-bound water, movable water, gas, and oil. For sea facies formation for which the pore-size and the rock matrix properties are uniform, NMR porosity is reasonably accurate. Using the current acquisition parameters: TW_L 12s TE_L =1.2ms for effective porosity, and TW_S 20ms TE_S =0.6ms for bound water porosity, we found good agreement between laboratory NMR porosity and that derived from conventional core analysis. However, we found that the porosity difference between NMR using such acquisition parameters and the core porosity logging is unacceptable in terrestrial formation in China; sometimes the difference is as big as 2 to 6 pu. This has prompted us to investigate the problem.

We analyzed NMR total porosity [2] measurement and the possible causes for the discrepancies in porosity measurement. Laboratory NMR measurements were carried out using the same parameters for data acquisition and processing as those used in Halliburton's MRIL logging. More than 40 samples with a wide range of porosities including artificial ceramic and sandstones were chosen to carry out the conventional and NMR porosity measurements. We found that when using current acquisition parameters, the porosity discrepancies for artificial ceramic and Berea sandstones were less than 1 pu, whereas those for the terrestrial sediment sandstones were very big. We found that when a new set of acquisition parameters was applied having TW_L 5s TE_L=0.9ms for effective porosity, and TW_S=10ms TE_S=0.3ms for bound water porosity, such discrepancies for terrestrial sandstones were reduced to less than 1 pu. This finding suggests that we may have to adjust acquisition parameters and data processing methods for different type of earth formations to obtain accurate NMR porosity.

NMR porosity measurement and data analysis

Measurement

The signal of NMR logging tool comes from hydrogen nuclei in the formation fluid. Water in micro-pores has a very short relaxation time and was difficult to detect by old NMR logging tools that had long echo spacing. Modern MRIL-P logging tool removed such a limitation. It has nine frequencies that can be divided into five frequency bands, i.e., 0,1,2,3, and 4, from low-frequency (far from the probe) to high-frequency (near the probe). The 0,1,2,3 frequency bands, each containing two frequencies, are used to detect effective porosity. The 4th frequency band has only one frequency, which is use to detect clay-bound water and its data acquisition parameters are fixed, i.e., wait time TW_S=20ms,

echo spacing TE_S=0.6ms, number of echoes NE=10, and number of scans NS=50.
The MRIL-P tool can see essentially all the fluids in the pore space near the wellbore, and the porosity measurement are characterized as being a "total porosity" measurement. A total porosity logging acquires two CPMG echo trains [3]: one fully and another partially polarized. The fully polarized echo train is acquired by using a long TW and a TE of 0.9 or 1.2ms. The echo train contains the signal of capillary-bound water and free water. The partially polarized echo train is acquired with a short TE of 0.6ms and a short TW of 20ms. This part of the spectrum represents the water signal from clay-bound water. This sequence consists of 50 echo trains each having 10 echoes [4]. The first two echo trains are usually discarded and the remaining 48 echo trains are stacked and used for computing the part of the decay spectrum that falls in the T_2 bins with T_2 less than 4ms. The two T_2 distributions (one from the fully polarized echo train and one from the partially polarized echo train) are spliced together to form a T_2 distribution from 0.5ms to more than 1,000 ms for the estimation of the total porosity.

Data processing

Reservoir rocks commonly exhibit a distribution of pore sizes and frequently contain more than one fluid type. Therefore, the spin-echo train recorded with a CPMG sequence does not decay with a single T_2 value but with multiple T_2 values [5] that can be described as

$$M(t) = \sum_i P_i \exp\left(-\frac{t}{T_{2i}}\right) \quad (i = 1\ \ 2\ \ 3\ \ \ldots\ldots) \tag{1}$$

Magnetization of the i^{th} component (P_i) at relaxation time of the i^{th} component (T_{2i}) can be inverted using equation 1. In practice, i is finite. The regular pass with an echo spacing of 1.2ms is usually fitted with a T_2 basis of 0.5, 1, 2, 4… 1024, 2048 ms, to obtain P_i i 1 2 … for a T_2 distribution.

Porosity calculation

Using a long TW_L of 12s and a TE_L of 1.2ms, the hydrogen nuclei in large-pore fluid are fully polarized and detected, leading to free fluid and large part of capillary bound water, whereas the signal of the hydrogen nuclei in micro-pore and clay-bound water is largely lost due to the long echo spacing. While using a TW_S of 20ms and a TE_S of 0.6ms, clay-bound water is fully polarized and detected, but other long T_2 components are suppressed, leading to predominantly clay-bound water signal. The T_2 distribution of 0.5, 1 and 2ms is concatenated with the supplemental part of the T_2 distribution obtained from the regular mode to form the total porosity T_2 distribution. This is defined as the area splicing method [6] (hereafter referred to as method I).

Partially polarized method is used to measure clay-bound water with a TW_S of 20ms and a TE_S of 0.6ms. It is fitted with 7 bins, where the T_{2i}'s are 0.5, 1.0, 2.0, 4.0, 8.0,16 and 256 ms;

- Fully polarized method is used to measure capillary-bound water and free fluids with a long TW_L of 12s and a TE_L of 1.2ms or 0.9ms. It is fitted with 12 bins, where the T_{2i}'s are 1, 2, 4 …1024, 2048 ms;
- The first 4 bins of clay-bound water is concatenated with the last 9 bins of capillary-bound water and free fluids, and their sum is described as total porosity, the first 3 bins as clay-bound water porosity, the last 10 bins as effective porosity.

The above approach is the empirical MRIL-P porosity measurement method. For the sandstones whose pore structures are simple, the difference between NMR porosity and core porosity are less than 1 pu When using this empirical method, so this method is suited to that kind of rocks. But for terrestrial formation where lithology and matrix components are complex, and pore structures are not simple, using the empirical method leads to large differences between NMR porosity and core porosity. We shall now address several possible factors that may cause such porosity discrepancy.

Influence factors

There are many factors that influence the NMR porosity measurement which can be described as follows:

Wait time (TW)

An improperly selected wait time (TW) is one of the main factors that influences NMR porosity. The basic aim is to fully polarize hydrogen nuclei using a long enough wait time without unduly reducing the logging speed. There are always a small quantity of hydrogen nuclei cannot be polarized fully even if $TW>3T_1$ leading to insignificant NMR porosity reduction.

Interecho time (TE)

If the TE is short enough to detect all clay-bound water (MCBW), and also can obtain the signal of capillary-bound water (MBVI) and free fluids (MBVM), then NMR total porosity (PHIT) equals to the sum of all partial porosities, that is:

$$\mathrm{PHIT} = \mathrm{MCBW} + \mathrm{MBVI} + \mathrm{MBVM} \tag{2}$$

The shortest TE of the current MRIL-P tool is 0.6ms, which is capable of detecting most signals of clay-bound water. However, it will still miss those components with relaxation times less than 0.6ms, leading to possible reduction in NMR porosity.

Light hydrocarbons or heavy oil

For formation containing oil, gas and water, NMR porosity Φ_{NMR} is the sum of water porosity ϕ_w ,oil porosity ϕ_o , and gas porosity ϕ_g as follows

$$\Phi_{NMR} = \phi(S_w + S_o HI_o + S_g HI_g) \tag{3}$$

Since the sum of the saturations of water, gas and water is 1 and the HI_o of light oil and

heavy oil is slightly less than 1 and the HI_g of gas is significantly less than 1, $\Phi_{NMR} < \Phi$. Therefore, the porosity calculated is less than the true porosity.

Paramagnetic minerals

The presence of paramagnetic minerals in the pore network or pore-solid interface cause strong internal field gradients which significantly shorten the T_2 relaxation times, leading to reduction in the apparent porosity.

T_2 splicing method

The parameters selection and bins splicing method may become one of the most important influence factors on the accuracy of MRIL-P porosity determination.

In all of the factors, the influence of TW and TE can be eliminated by suitable job planning. The influence of light hydrocarbons, heavy oil and paramagnetic minerals can be eliminated by correction with standard procedure. This paper is focused on splicing method and its impact to the determination of accurate formation total porosity.

Results and discussions

We found that when the same acquisition parameters as those of Halliburton's MRIL logging were used, the differences between NMR and conventional core porosities in artificial ceramic and Berea sandstones were less than 1 pu, but such differences for the terrestrial sediment sandstones were very big, about 3-5 pu. We believe that it is because of the matrix components and pore distributions are uniform for artificial ceramic and Berea sandstones, but quite complex for terrestrial sediment. The latter contains micro-pores which were not detected when using a TE_S of 0.6ms, leading to a reduction in the apparent porosity. We therefore suggest the following acquisition parameters to address the terrestrial formation in China (hereafter referred to as method II)

1. Partially polarized method is used to measure clay-bound water with a TW_S of 10ms and a TE_S of 0.3ms. It is fitted with 6 bins, with T_{2i} being 0.25 0.5 1.0 2.0 4.0 16 ms;

2. Fully polarized method is used to measure capillary-bound water and free fluids with a long TW_L of 5s and a TE_L of 0.9ms. It is fitted with 12 bins, with T_{2i} being 1, 2, 4, …1024, 2048 ms;

3.The first 4 bins of is concatenated with the last 10 bins of , and the sum is designated as the total porosity with the first 3 bins as clay-bound porosity and the last 11 bins as effective porosity.

These samples with a wide range of porosity including artificial ceramic, Berea sandstones, sandstones in Daqing and Xinjiang and Dagang were chosen to carry out the NMR porosity measurements. As indicated in Figure 1, when method I was used, the differences between NMR porosity and core porosity in artificial ceramic and Berea sandstones were less than 1 pu.

In Figure 2, the results of both methods I and II for sandstones in Daqing were shown. The porosity discrepancies were 2-5 pu for method I, but less than 1 pu for method II.

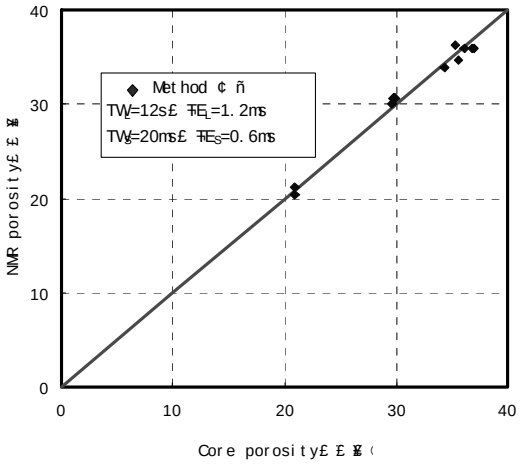

Figure 1. The contrast of NMR porosity and core porosity in artificial ceramic and Berea sandstones

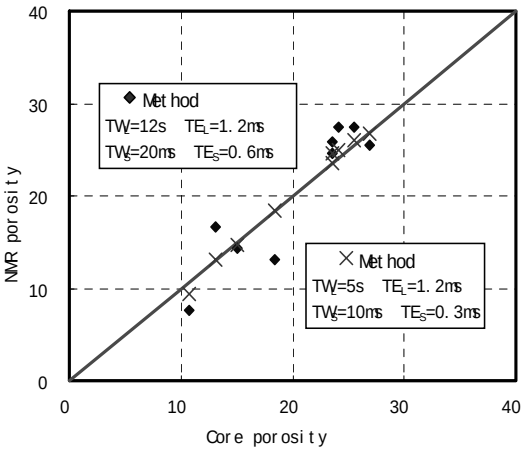

Figure 2. The contrast of NMR porosity and core porosity in sandstones in Daqing

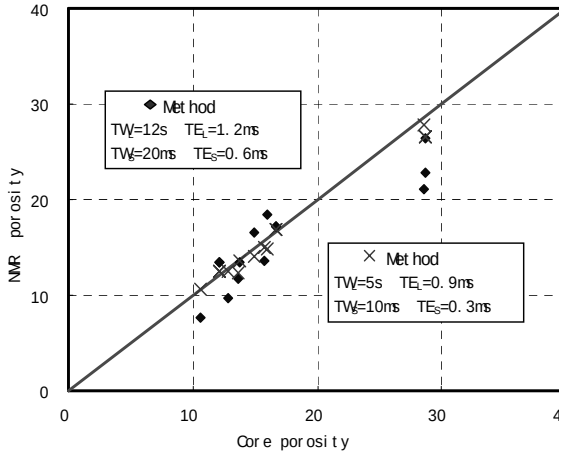

Figure 3. The contrast of NMR porosity and core porosity in sandstones in Xinjiang

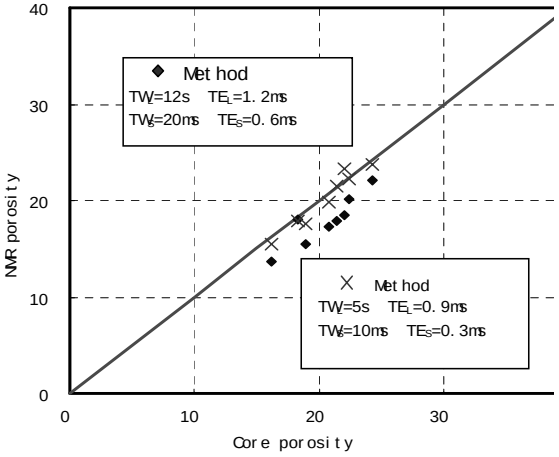

Figure 4. The contrast of NMR porosity and core porosity in sandstones in Dagang

Similarly in Figure 3, the results of methods I and II for sandstones in Xinjiang were displayed. Again, the porosity discrepancies for method I were 2-6 pu, whereas those for method II reduced to less than 1 pu for most of them. As shown in Figure 4, when simulate current data acquisition and processing method, the difference between NMR porosity and core porosity are 2-4 pu. And less than 1 pu for method II, the difference is acceptable. From the contrast plot between core porosity and NMR porosity we can found that when use the current data acquisition and processing method, the difference between core porosity and NMR porosity in the most of rocks are big, see to 2-6. However, when use the method that this experiment selected, the difference is less than 1 expect for two rocks.

It is obvious that the method that this experiment selected is suitable for terrestrial formation in China and can obtain more accurate formation total porosity.

Conclusions

I. The current data acquisition and processing method only suitable for the large porosity formation that the matrix components and pore-structure are uniform but not for terrestrial formation in China.

. The terrestrial formation in China differs from different regions, if the same acquisition parameters are used for different regions, it will lead to big difference between core porosity and NMR porosity. Therefore, it is suggested that we need carry out core analyzing before logging, obtain suitable parameters, and then can obtain accurate NMR porosity.

. From this work, we can draw a conclusion that we cannot apply the empirical approach to terrestrial formation simply, but should set up a set of total porosity data acquisition and processing method which is suitable for the terrestrial formation in China. According to the core samples selected in this experiment, we provide a set of NMR data acquisition and processing method: The new acquisition parameters for terrestrial sandstones are applied as TW_L 5s TE_L=0.9ms for effective porosity, and TW_S=10ms TE_S=0.3ms for bound water porosity, and the bins of clay-bound water as 0.25 0.5 1 2 4 16. We found that when the new method is applied, the accuracy of NMR total porosity is significantly improved.

References

[1] George R. Coates etc. NMR Logging Principles and Applications. Houston, 1999

[2] M.G.Prammer,E.D.Drack etc. “Measurements of Clay-bound Water and Total Porosity by Magnetic Resonance Logging”, SPE-36522, The Log Analyst,v.37,p.61,1996

[3] K-J Dunn and D.J.Bergman . “A Method for Inverting NMR Data Sets with Different Signal to Noise Ratios” SPWLA 39th Annual Logging Symposium, May 26-29, 1998

[4] Songhua Chen and Daniel T.Georgi. “Improving the Accuracy of NMR Relaxation Distribution Analysis in Clay-rich Reservoirs and Core Samples”. SCA-9702, 1997

[5] Lizhi Xiao. NMR Logging Interpretation and Applications. Beijing, 1998

[6] Lizhi Xiao, Xiyuan Chai and Baoxi Sun. NMR Logging Interpretation and China Case Studies. Beijing, 2001