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A method to determine nuclear magnetic resonance (NMR) T_2cutoff based on normal distribution simulation in tight sandstone reservoirs

Liang Xiao[a,b,c,*], Junran Li[c], Zhiqiang Mao[d], Jun Lu[e,*], Hongyan Yu[f], Haopeng Guo[g], Gaoren Li[g]

[a] Key Laboratory of Geo-detection, China University of Geosciences, Ministry of Education, Beijing, PR China
[b] School of Geophysics and Information Technology, China University of Geosciences, Beijing, PR China
[c] Department of Geosciences, The University of Tulsa, Tulsa, OK, USA
[d] State Key Laboratory of Petroleum Resource and Prospecting, China University of Petroleum, Beijing, PR China
[e] McDougall School of Petroleum Engineering, The University of Tulsa, Tulsa, OK, USA
[f] Northwest University, Xi'an, Shaanxi, PR China
[g] Research Institute of Exploration & Development, Changqing Oilfield, PetroChina, Xi'an, Shaanxi, PR China

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ABSTRACT

The T_2cutoff is an important input parameter in nuclear magnetic resonance (NMR) applications. The accuracy of the T_2cutoff affects the prediction reliability of parameters associated with the identification and evaluation of formations. Current methods are based on regional statistics; they have limited applications and the predicted values are not always reliable. In this study, a total of 36 core samples, drilled from Triassic tight sandstone reservoirs of the southwest Ordos Basin in China, were used for laboratory NMR measurements under fully brine saturated and irreducible water conditions. Based on the morphological character analysis of experimental NMR T_2 spectra, we demonstrate that NMR T_2 spectra can be fully simulated using the normal distribution function. In addition, a new method was proposed, which can predict various T_2cutoffs based on the morphological differences of NMR T_2 spectra, and the irreducible water saturation (S_{wirr}) was calculated, which represents the ratio of the sum volume of clay bound water and capillary bound water to total pore volume. The reliability of this method was verified by comparing the predicted T_2cutoff and S_{wirr} values with those of core NMR experimental results. Finally, we extended this method into field applications in several tight sandstone reservoirs in China. The results show that total T_2 distributions of the formation were fully simulated by the normal distribution function, and various T_2cutoff and S_{wirr} values were precisely predicted. Meanwhile, tight sands permeability curves, predicted based on the Timur-Coates model, were also accurately estimated. The results of our study may be applied to improve tight sandstone reservoir identification and evaluation using NMR logs.

1. Introduction

Statistical histograms of core porosity and permeability illustrate that the Triassic sandstone reservoirs in the southwest Ordos Basin, northwest China, are typical tight sandstone reservoirs (Fig. 1) [1]. The porosities range from 6% to 12%, with more than 80% of core samples having less than 10% porosity (Fig. 1a), and permeabilities predominantly range from 0.01 mD to 3.16 mD, with more than 88% less than 1.0 mD (Fig. 1b). The formation also exhibits a complicated pore structure, strong heterogeneity, and various water salinities [2–3]. As a result, the identification and evaluation of tight sandstone reservoirs (e.g., effective porosity, water saturation, permeability, and pore structure evaluation) based on conventional well logs involves significant challenges [4–5].

Nuclear magnetic resonance (NMR) logs, developed in the 1990 s, play an important role in the evaluation of tight sandstone reservoirs [6–7]. The NMR log is superior to conventional well logs because it can offer several precise parameters for the identification and evaluation of formations, such as effective porosity, irreducible water saturation (S_{wirr}), free fluid volume, and permeability [8]. The predicted results can therefore avoid the effect of formation lithology and saturated fluids [9]. More importantly, an NMR log can be used to quantitatively evaluate formation pore structure [10–12].

During formation evaluation, the accuracy of evaluated results is mainly determined by the value of the T_2cutoff [13–14]. The T_2cutoff is defined as a T_2 time, which generally divides the entire NMR T_2 spectrum into two parts; the corresponding rock pores are separated into two radii [15–16]. A T_2 distribution with T_2 times below the T_2cutoff

* Corresponding authors at: School of Geophysics and Information Technology, China University of Geosciences, Beijing, PR China (L. Xiao).
E-mail addresses: xiaoliang@cugb.edu.cn (L. Xiao), jun-lu@utulsa.edu (J. Lu).

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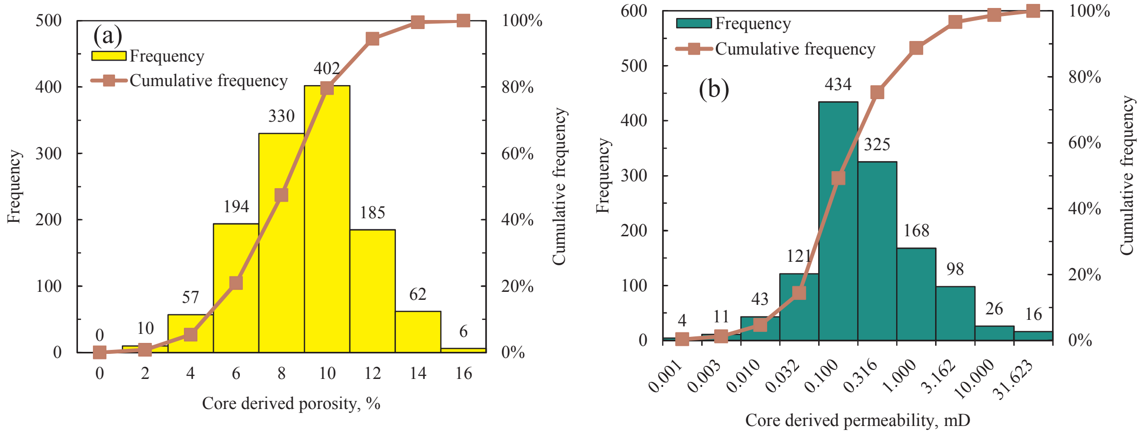

Fig. 1. Statistical histograms of core porosity (*a*) and permeability (*b*) in the Triassic tight sandstone reservoirs of the southwest Ordos Basin, northwest China.

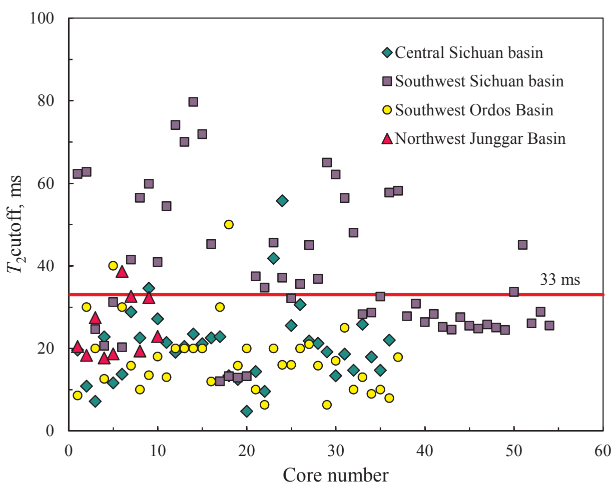

Fig. 2. Histogram of T_2cutoff values acquired from experimental NMR results of core samples drilled from four tight sandstone reservoirs in China.

value represents small rock pores with irreducible water occupying the pores (including clay irreducible water and capillary bound water). These fluids are not producible due to their occupied small pore size and poor pore connectivity. On the contrary, a T_2 spectrum with T_2 relaxation times above the T_2cutoff represents large rock pores occupied by free fluids (e.g., free water and/or hydrocarbon). Therefore, the T_2cutoff is an important indicator of irreducible water and movable fluids, and a key input parameter when calculating irreducible water saturation and permeability from NMR logs [16].

Frequently, fixed values of 33 ms and 92 ms are defined as the T_2cutoff for sandstone reservoirs and carbonate reservoirs, respectively. These values were initially acquired from laboratory NMR experiments of core samples drilled from the Wilcox area of the Gulf of Mexico and western oilfields in Canada [17–20]. These T_2cutoff values have long been used in conventional reservoirs around the world [13–14,21]. However, an increasing number of field applications have shown that 33 ms is not always a reasonable T_2cutoff value, especially for low permeability to tight sandstone reservoirs [22]. Many studies have also pointed out that NMR T_2 distributions are influenced by various factors such as lithology, porosity and pore distribution, pore fluids, and saturated water salinity [16,23–24], suggesting that the T_2cutoff should not be universal. For example, the core samples drilled from tight sandstone reservoirs in China were highly variable; T_2cutoff values were not close to 33.0 ms or any other fixed value (Fig. 2). To improve the application of NMR logs to formation evaluation, various T_2cutoffs applicable to different types of formations should be used.

The NMR experiment is considered to be the most accurate method in determining the T_2cutoff. However, this method can only be applied to limited core samples; therefore, the acquired T_2cutoffs cannot be used to represent entire formations [25]. Instead, many studies have attempted to develop various T_2cutoffs for field NMR applications [23–24,26–37]. Parra et al. (2001) investigated the vuggy Florida carbonate using the FZI method and found different fixed T_2cutoffs in different types of formation [23]. Wu et al. (2014) first classified formations based on their lithological differences and determined various fixed T_2cutoffs for each type of formation based on core experiments [24]. In these two methods, although several T_2cutoffs were used, the effects of many other factors (e.g., pore size, pore distribution, formation depth) were not considered. Additionally, a single T_2cutoff was still used for similar formations.

Many other studies have proposed methods for determining T_2cutoff values. For example, by considering the effect of lithology on the T_2 spectrum [26]; using a tapered model [27]; combining NMR and capillary pressure data [28]; investigating the effect of temperature [29]; establishing a model based on the amplitude and geometric mean of the last peak in the spectrum [30–32]; deriving a statistical relationship among core derived T_2cutoffs, porosity, and permeability, [33]; using the formation pressure [34]; employing CEC data [35]; combining NMR with modular formation dynamics tester (MDT) data [36]; using magnetic susceptibility data [37]; and applying multifractal theory [16]. Although these methods made progress in determining T_2cutoff values in NMR applications, they are all statistical methods based on the NMR experiments of core samples; thus, these methods cannot be used to determine various T_2cutoff values for field applications. Meanwhile, no relationship between T_2 spectrum shapes and T_2cutoff values has been presented. In summary, these methods are only regionally effective and are not applicable to other formations.

The purpose of this study was to develop a new method that can be widely used to predict various T_2cutoffs based on the characteristics of the NMR T_2 spectrum. This method was established based on 36 core samples drilled from Triassic tight sandstone reservoirs of the southwest Ordos Basin, China. We also extended this method to field applications in order to calculate accurate S_{wirr} and permeability values in many other regions.

2. NMR experiments and data analysis

2.1. Physical properties of core samples

The physical properties of the 36 experimental core samples are listed in Table 1. Among these properties, core-derived porosities were acquired using the helium injection method and permeabilities were measured using an instantaneous-pulse permeability-test method