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Research Article

NMR logging activation sets selection and fluid relaxation characteristics analysis of tight gas reservoirs: A case study from the Sichuan Basin☆,☆☆

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Abstract

With complex lithology and reservoir types, as well as high concealment and heterogeneity, tight reservoirs in the Sichuan Basin involve significant uncertainties in gas–water relationship. Since NMR logging can effectively solve problems related to the multiple results of conventional logging operations, it can be deployed for accurate assessment of the properties of formation fluids. Accordingly, different NMR logging activation sets were assessed in accordance with the specific features of tight reservoirs in the basin. With consideration to NMR logging data obtained under different activation sets and testing data of wells, the optimal NMR logging activation set was identified. Moreover, with relaxation characteristics of rocks, gas and water as theoretical foundations, the T_2 gas and water relaxation characteristics were reviewed to highlight the impacts of porosity, pore sizes, fluid properties and other factors of tight reservoirs on T_2 horizontal relaxation distribution. According to the research results, D9TWE3 can be seen as the most suitable NMR logging activation set for tight reservoirs in the Sichuan Basin; reservoir tightness is the key influence factor for the distribution of gas/water relaxation in tight clastic reservoirs; generally, in tight sandstone reservoirs, natural gas shows a longer T_2 relaxation time than water; in fracture-vug type carbonate reservoirs, the right peak of T_2 distribution spectrum of gas layers is frontal, while the right peak in T_2 distribution spectrum of water layers is backward. In conclusion, the standards for gas/water relaxation in tight sandstone and carbonate reservoirs in the Sichuan Basin can help effectively determine the physical properties of fluids in tight reservoirs with porosity of 4–10%. Such standards provide reliably technical supports for gas/water identification, reserves estimation and productivity construction in tight reservoirs of the Sichuan Basin.

Keywords: Sichuan basin; Tight sandstone; Carbonate; NMR logging; Activation set; Rock relaxation; Gas/water relaxation; Fluid property

The Sichuan Basin has abundant natural gas resources. With the progress of exploration, the operations are facing more and more complex targets. Tight reservoirs such as tight sandstone and carbonate have become the key exploration targets in the new era.

Tight reservoirs in the Sichuan Basin have strong heterogeneity and poor physical properties. For most of tight reservoirs, the porosity is less than 10%, and the permeability is less than 0.1 mD, which make them tight or extremely tight reservoirs with complex gas–water relationship.

In view of the characteristics of tight reservoirs in the Sichuan Basin, gas/water identification is the difficult point in the evaluation of tight reservoirs. NMR logging can correctly evaluate the fluid properties [1,2] of tight reservoirs such as tight sandstones and carbonate rocks, but the premise is that a reasonable NMR logging activation set must be available.

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The identification standard for T_2 gas/water relaxation of tight sandstone and carbonate reservoirs in the Sichuan Basin are proposed with relaxation characteristics of rocks, gas and water as theoretical foundations in this paper. With this standard, fluid properties of tight reservoirs with a porosity of 4–10% can be identified effectively, which provides reliable technical supports for gas/water identification, reserves estimation and productivity construction in tight reservoirs of the Sichuan Basin.

1. Selection of NMR logging activation set

There are 4 types of MRIL-Prime logging activation sets, i.e. single TW/single TE mode, dual TW/single TE mode, single TW/dual TE mode, and dual TW/dual TE mode. These activation sets lay a foundation for the application of P type NMR in different reservoir conditions and different observation objects. A suitable activation set should be selected depending on specific reservoirs, reservoir types and exploration layers [3].

By far, several contrast tests have been conducted on the NMR logging activation sets with the tight clastic rocks of the Upper Triassic Xujiahe Fm in the Sichuan Basin. Taking the activation sets comparison of Xujiahe Fm in Well X10 as an example, 4 logging activation sets data were collected [4], including D9TW3, D9TWE1, D9TWE2 and D9TWE3. These 4 activation sets correspond to different waiting time and echo interval (Table 1). In this study, the NMR logging data of different activation sets were treated respectively, and their comparison and analysis were made as follows.

1.1. Comparison of "dual TW/single TE" mode and "dual TW/dual TE" mode

Two activation sets of NMR logging data were collected from 3697 m to 3731 m of Xujiahe Fm in Well X10, that is, D9TW3 and D9TWE3. The corresponding parameters show that, the long waiting time of Group A is consistent with the short waiting time of Group B; however, the echo intervals are different significantly – the echo interval of Groups A and B is 3.6 ms under D9TW3, and 0.9 ms under D9TWE3.

According to the spectral distribution characteristics of this reservoir interval, when D9TW3 is used, the corresponding echo interval is larger, the right boundary in the long and short waiting time T_2 distribution spectrum has a left shift, the range of T_2 spectrum is narrowed, and differential spectrum indicates weak movable hydrocarbon; when D9TWE3 is used, the corresponding echo interval is smaller, the range of the long and short waiting time T_2 spectrum is wider, and differential spectrum indicates stronger movable hydrocarbon (Fig. 1). According to the long waiting time T_2 spectrum, the movable fluid calculated by D9TW3 is mainly moveable water, and the movable gas calculated by D9TWE3 is more than that calculated by D9TW3. This reservoir interval was tested through casing perforation and sand fracturing, and revealed a gas yield of 0.5246×10^4 m^3/d and a water yield of 6.2 m^3/d, so this interval should be evaluated as a gas–water layer [5]. Comprehensive comparative analysis shows that the reservoir moveable fluid indicated by D9TWE3 is consistent with the actual test situation. Therefore, D9TWE3 mode is better than D9TW3 mode.

Table 1
Four activation sets of MRIL-Prime logging tool and their basic parameters.

Activation sets		*TW*/s	*TE*/ms	*NE*/m
D9TW3	D9TW3ABC	13.0/1.0	3.6	125
D9TWE1	D9TWE1ABC	13.0/1.0	0.9	500/500
	D9TWE1ADC	13.0	0.9/1.8	500/250
D9TWE2	D9TWE2ABC	13.0/1.0	0.9	500/500
	D9TWE2ADC	13.0	0.9/2.7	500/166
D9TWE3	D9TWE3ABC	13.0/1.0	0.9	500/500
	D9TWE3ADC	13.0	0.9/3.6	500/125

1.2. Comparison of "dual TW/dual TE" modes

Three "dual TW/dual TE" modes for NMR logging data collection and echo signal analysis were tested in this study, including D9TWE1, D9TWE2 and D9TWE3 modes. All these 3 modes have long enough waiting time, that is, $TW = 13.0$ s, after which its spin echo signal was fully restored to the state of balance. Since the recovery time is influenced by logging speed, the logging speeds of these 3 modes for test well are all set at 1.5 m/s, with a purpose of polarizing the hydrogen nuclei in the pores.

Considering the influence of waiting time and echo interval on NMR logging, long and short waiting time, and echo interval (dual TW) of these 3 activation sets were kept consistent, so the achieved differential spectrum is basically the same. Since gas reservoir is the main type of tight reservoir in the Sichuan Basin, diffusion coefficient plays a major role. To highlight the information of natural gas, based on the difference of "dual TE" of 3 activation sets, including D9TWE1, D9TWE2 and D9TWE3, combined with gas test material, we processed, compared and analyzed the original NMR echo signal of the tight gas layer; finally, the most suitable activation set was selected. In this way, the gas reservoir with a porosity of 4–10% can be identified effectively, in order to deploy accurate assessment of the properties of fluids in tight reservoirs, such as tight clastic rocks and carbonate rocks, in the Sichuan Basin.

Taking the tight reservoir interval of 4513–4552 m in Well X10 as an example (Fig. 2), its lithology is gray fine sandstone, gas logging total hydrocarbon increases from 0.85% to 51.357%, and the porosity ranges from 4% to 10%. D9TWE1, D9TWE2 and D9TWE3 activation sets were employed in the collection of original NMR logging data, and the corresponding parameters show that the waiting time and echo interval of Groups A and B is consistent with that of Group D. Only the long echo interval of Group D of these 3 activation sets are respectively 1.8 ms, 2.7 ms and 3.6 ms (Table 1).

The processed results of the echo signal of 3 activation sets were compared (Fig. 2). For the echo signal from the interval of 4513.5–4517.4 m collected by D9TWE3 mode, after deconvolution, the long echo interval T_2 spectrum of Group D