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RESEARCH PAPER

A tight sandstone trapezoidal pore oil saturation model

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Abstract: "Non-Archie" phenomena are common in tight sandstone reservoirs with complicated pore structure, bringing challenges to the logging evaluation of tight sandstone. Based on the characteristics of tight sandstone pore structure, a new trapezoidal pore saturation model considering the effect of pore structure on rock conductivity is presented, in which the pore in tight sand is divided into straight pore with constant cross-sectional area and trapezoidal pore with variable cross-sectional area, and the total rock resistance is taken as the parallel resistance of these two parts to compressively consider the influence of pore structure and conductive volume on rock conductivity. The model parameters are studied by reconstructing the trapezoidal pore structure. Based on the trapezoidal pore reconstruction, characterization methods of model parameters were studied under the constraint of rock electrical properties test, and the variation was revealed of tortuosity, straight pore proportion and trapezoidal factors. The model was used in logging evaluation of tight sandstone of several wells, the results show the oil saturation obtained from the new model considering the effect of pore structure on electrical properties from the aspects of pore length and pore cross-section is in good accordance with the real regularity and petrophysical characteristics of the reservoir, and much closer to the formation oil-bearing conditions than that from the Archie model.

Key words: Ordos Basin; Triassic Yanchang Formation; tight sandstone; pore structure; trapezoidal pore; saturation model

Introduction

Extensive in distribution and abundant in resources, tight oil is an important domain of global oil and gas exploration and development[1–4]. With complex pore structure, tight reservoirs have non-Archie phenomenon frequently, namely, resistivity index and water saturation showing a non-linear relationship in the double logarithm coordinates. In this case, the existing evaluation models are no longer suitable for tight sandstone reservoir[5], making oil saturation evaluation of tight reservoirs difficult. It is well-known that complex pore structure in reservoirs is associated with complex conductive responses. Owen, Diedreix, Swanson and Crane[6–9] revealed the complex conductive laws in complex pore structure rock by physical experiment and numerical simulation. Mao Zhiqiang, Tao Guo and Wang Kewen et al.[10–12] further clarified this relationship in the typical complex pore structure reservoirs in China. It can be seen that domestic and foreign scholars have reached consensus on the causes of the complex conductive law in tight sandstone, but no quantitative model has been established to meet the needs of tight reservoir saturation evaluation. Consequently, tight oil saturation evaluation in field site still uses the variable parameter Archie model, resulting in large errors in the predicted values. In view of the problem of saturation evaluation in tight sandstone reservoirs, the concept of trapezoid pore and its model have been advanced to characterize complex pore structure based on the study of pore structure of tight sandstone, and TPM model (trapezoidal pore model) has been proposed to characterize the "non-Archie" phenomenon; calculation methods of parameters in the model are given according to numerical simulation, in the hope of improving the accuracy of quantitative evaluation of oil and gas saturation in tight sandstone reservoirs.

1. "Non-Archie" phenomenon and problem of tight sandstone saturation evaluation

In 1942, Archie published the Archie model[13], which firstly gives the relationship between the reservoir oil and gas content and its conductivity response, laying a solid foundation for quantitative evaluation of oil and gas content by well logging. The typical characteristic of the Archie model is a linear relationship between resistivity index and water saturation in the double logarithmic coordinates, which is common in Berea sandstone (high porosity and high permeability), as shown in Fig. 1a. However, different from Berea sandstone,

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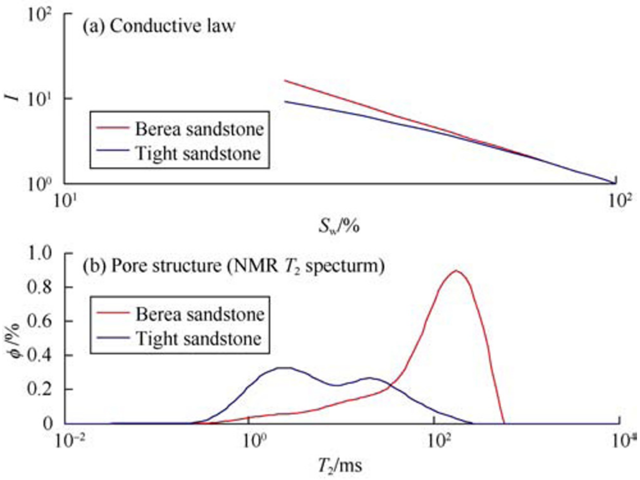

Fig. 1. Contrasts of conductive law and pore structure between tight sandstone and Berea sandstone.

this relationship in tight sandstone takes on a downward curve shape, as shown in Fig. 1a.

Previous studies have shown that the nonlinear relationship between resistivity index and water saturation of tight sandstone in the double logarithmic coordinates was caused by the complicated pore structure[7–8, 14–17]. Fig. 1b shows NMR experimental results of two samples corresponding to Fig. 1a, pore distribution of Berea sandstone is shown in Fig. 1b (red line), featuring a single-peak T2 of large pores and simple pore structure. Whereas pore structure of the tight sandstone sample is obviously different from that of Berea sandstone (Fig. 1b blue line), with a double-peak T2 indicating rich micro-pores and complex pore structure. Fig. 1 and a large number of digital rock physics simulation results show that it is the differences in pore structures between rocks, or even between different pore ranges of the same rock that cause conductive response differences, resulting in the "linear" and "nonlinear" relationship difference between high porosity and permeability sandstone and tight sandstone. In this paper, the nonlinear relationship between resistivity index and water saturation is called "non-Archie" phenomenon. The above analysis shows that the Archie model is suitable only for sandstone of simple pore structure, whereas the "non-Archie" phenomenon must be explained by establishing a new tight sandstone saturation model.

At present, tight sandstone saturation evaluation is still done with Archie model or its extended forms in the field practice, there are two main ideas[7, 18–20]: (1) Archie formula of variable parameters, but this method has obvious defects in tight sandstone, since the tight oil reservoir has a so high oil saturation (70%–80%), which lab experiments cannot reach, the model parameters fitted from this experiment data are not reliable; (2) using the extended Archie model forms in which the pores will be divided into several pore parts until conductive relationship of every part can be expressed by Archie model, and sum together conductive expression of all pore parts to get the total conductive expression. However, this method may easily lead to an unfixed form of saturation model, and bring more model parameters, which may limit its wide application.

In order to meet the requirement of logging evaluation of tight oil reservoirs, it is imperative to clarify the relationship between the pore structure and conductive response, and establish a new saturation model for tight sandstone reservoirs.

2. Pore structure characteristics of tight sandstone

As unconventional oil and gas reservoirs with complex pore structure have become important targets for oil and gas exploration, analysis of pore structure characteristics has gradually become one of the core contents in the conductivity response law study. The pore structure is mainly shaped by sedimentation and diagenesis, sedimentation determines the congenital conditions of pore development, whereas diageneses, including compaction, cementation and dissolution, dictate the final characteristics of pore structure[21]. Based on micro CT, QEMSCAN and MAPS, the pore structure characteristics of tight sandstone cores in Ordos Basin and Songliao Basin have been examined, which reveals that tight sandstone is the result of strong compaction, strong cementation and weak dissolution[22]. Consisting of fine particles in linear contact after strong compaction mostly, the tight sandstone reservoirs have small pores and narrow throats in poor connectivity (Fig. 2a). Dissolved pores improve the physical properties of the tight reservoirs by making the throats wider and improving the connectivity of pores and throats (Fig. 2b). Under tectonic stress, micro fractures would form when brittle minerals are broken by extrusion (Fig. 2a). In addition, a large amount of clay micro-pores are formed when a high content of interstitial materials fill in intergranular pores (Fig. 2c, d, e). In a word, tight sandstone reservoirs have a pore-throat structure of residual intergranular pores, feldspar dissolving pores and clay micro pores. Most of the pores in the reservoir are controlled by fine throats, greatly weakening the reservoir seepage ability, and bringing about complex conductive response laws [23].

From the aspect of pore throat connectivity, in tight sandstone with mostly micro-pores, two kinds of pore throat combination usually exist, (1) pore-throat combination of big pore and micro-throat with greatly variable cross-sectional area, acting as the main seepage channel, and (2) pore-throat combination of micro-pore and micro-throat with constant cross-sectional area. The above two kinds of pore throat combinations can represent all seepage channels in the porous media, which is the foundation for establishing tight sandstone saturation model.

3. Trapezoidal pore concept based on conductive theory of porous media and its resistance derivation

3.1. Trapezoidal pore concept

The definition of resistance shows that the resistance of