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Research article

Quantitative calculation of GOR of complex oil-gas-water systems with logging data: A case study of the Yingdong Oil/Gas Field in the Qaidam Basin☆

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Abstract

In the Yingdong Oil/Gas Field of the Qaidam Basin, multiple suites of oil-gas-water systems overlie each other vertically, making it difficult to accurately identify oil layers from gas layers and calculate gas-oil ratio (GOR). Therefore, formation testing and production data, together with conventional logging, NMR and mud logging data were integrated to quantitatively calculate GOR. To tell oil layers from gas layers, conventional logging makes use of the excavation effect of compensated neutron log, NMR makes use of the different relaxation mechanisms of light oil and natural gas in large pores, while mud logging makes use of star chart of gas components established based on available charts and mathematical statistics. In terms of the quantitative calculation of GOR, the area ratio of the star chart of gas components was first used in GOR calculation. The study shows that: (1) conventional logging data has a modest performance in distinguishing oil layers from gas layers due to the impacts of formation pressure, hydrogen index (HI), shale content, borehole conditions and invasion of drilling mud; (2) NMR is quite effective in telling oil layers from gas layers, but cannot be widely used due to its high cost; (3) by contrast, the star chart of gas components is the most effective in differentiating oil layers from gas layers; and (4) the GOR calculated by using the area ratio of star chart has been verified by various data such as formation testing data, production data and liquid production profile.

Keywords: Qaidam Basin; Yingdong Oil/Gas Field; Mud logging; Logging; Excavation effect; NMR; Oil and gas layer differentiation; GOR

1. Introduction

Located in the Yingxiongling region of the western Qaidam Basin, the Yingdong Oil/Gas Field ranks the second among the four integral oil and gas fields discovered there in recent years, the production of which all reach hundred million tons. It features long hydrocarbon-bearing intervals, large cumulative thickness of oil and gas layers [1] and relatively thin single layers. Oil and gas layers are difficult to identify due to the well-developed faults in the Yingdong Oil/Gas Field [2] and the vertical stacking of multiple oil-gas-water systems. Gas layers are perforated as oil layers now and then, which greatly increases the pressure of surface oil lines. Meanwhile, oil/gas reservoir pressure decreases rapidly due to the production of high GOR reservoirs. The above-mentioned factors are not good for the development of these reservoirs. Therefore, it is urgent to address the issue of oil and gas layer identification and quantitative GOR calculation for the Yingdong Oil/Gas Field.

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2. Reservoir overview

2.1. Reservoir lithology and petrophysical properties

The reservoirs are medium in compositional maturity, medium–high in textural maturity, fine in grain size, low in matrix content, medium-low in cement content, and weak in diagenesis. Reservoir rock, relatively stable in type, is lithic feldspar sandstone. Fine in grain size, the sandstone is mainly medium sandstone-siltstone, with an average cement (mainly calcite) content of 7%. The reservoir pores are well-developed and quite even in distribution with fine connectivity. The reservoir space is composed of intergranular pores, followed by dissolution pores and a small amount of fissures, accounting for 81.7%, 15.5% and 2.8% respectively. The reservoirs have a porosity of 10.0%–23.0%, 20.4% on average, and a permeability of 0.1–500 mD, 124.9 mD on average.

2.2. Reservoir temperature and pressure

The reservoirs have a geothermal gradient of 3.08 °C/(100 m), representing normal temperature system. According to the field measured 26 data points of temperature versus depth, the fitted formula of temperature and depth is written as:

$$T = 10.428 + 0.0308D(R = 0.9550) \quad (1)$$

where T is formation temperature, °C; D is formation depth, m.

The formation pressure gradient is 1.07 MPa/(100 m), representing normal pressure system. According to the field measured 26 data points of pressure versus altitude, the fitted formula of pressure and altitude is written as:

$$p = 31.479 + 0.0107H(R = 0.9849) \quad (2)$$

where p is formation pressure, MPa; H is altitude of measured point, m.

2.3. Reservoir oil and gas properties

The surface crude is identified as light medium-viscosity oil, with an average density of 0.842 t/m^3, average viscosity of 9.4 mPa s, average paraffin content of 14.0%, average gasoline content of 10.1%, average kerosene & diesel content of 28.3%, average setting point of 30.0 °C, average wax precipitation point of 45.0 °C, and average initial boiling point of 144.0 °C. The oil PVT test demonstrates that the DGOR (dissolved gas-oil ratio) is 20.7–99.0 m^3/m^3, 74.0 m^3/m^3 on average under original formation pressure.

The gas has a relative density of 0.638, average methane content of 88.05%, average ethane content of 3.78%, average propane content of 1.63%, average heavy hydrocarbon content C_4^+ of 1.48%, average nitrogen content of 4.65%, and average carbon dioxide content of 0.41%. The gas PVT test shows that the gas has a volume factor of 0.007 08–0.011 93, density of 0.061–0.101 t/m^3, viscosity of 0.013 7–0.015 6 mPa s, and deviation factor of 0.837 9–0.870 1 (0.854 0 on average) under original formation pressure, representing dry gas.

3. Qualitative identification of oil and gas layers

3.1. Differentiation of oil and gas layers with conventional logging

Resistivity [3] and excavation effect of compensated neutron logging [4,5] are often used to identify oil and gas layers in conventional logging.

However, the resistivity of oil and gas layers principally reflects reservoir petrophysical properties rather than oil or gas properties when the oil and gas layers have similar water saturation. In addition, the invasion depth of fresh water drilling fluid varies significantly due to relative high formation water salinity in the Yingdong Oil/Gas Field and relatively large petrophysical difference of different reservoirs. Resistivity mainly reflects reservoir petrophysical properties and drilling fluid invasion under comparative water saturation [6], but doesn't show obvious differences between oil layers and gas layers, so resistivity is not suitable for the Yingdong Oil/Gas Field.

The excavation effect of compensated neutron logging method is based on the assumption that the compensated neutron logging porosity will decrease and the apparent porosity of acoustic and density loggings will increase in gas layers, so there will be some differences between the porosity measured by compensated neutron logging and the apparent porosity measured by acoustic and density loggings in gas layers. However, different gas layers are different in formation

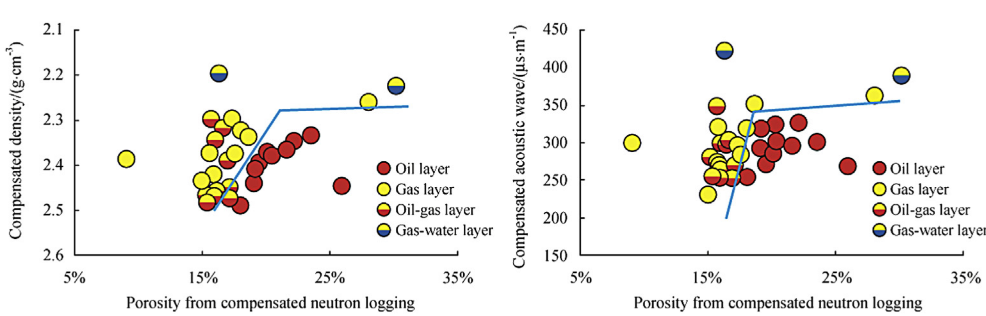

Fig. 1. Oil and gas layer identification crossplot with excavation effect of compensated neutron logging.

pressure, hydrogen index and density [7]; meanwhile, the three-porosity curves are also influenced by shale content, lithic component content and other factors, thus covering gas responses to some extent. In addition, the frequent borehole enlargement in sandstone and mudstone formation would lower the quality of the measured three-porosity data. Fig. 1 is identification crossplot for oil and gas layers with excavation effect of compensated neutron logging. It can tell oil layers from gas layers in regular borehole intervals with qualified three-porosity curves, but can not identify oil-gas layers.

3.2. Oil and gas layer identification with NMR

NMR has unique functions in describing reservoir pore structures [8]and fluid properties [9,10]. The transverse relaxation time (T_2) measured by NMR can be expressed as [11]:

$$\frac{1}{T_2}=\frac{1}{T_{2B}}+\frac{D(\gamma G T_E)^2}{12}+\rho_2\frac{S}{V} \tag{3}$$

where, $T_{2\mathrm{B}}$ is relaxation time of fluid volume, ms; D is diffusion coefficient, μs^2/ms; G is magnetic field gradient, Gs/cm; T_E is echo spacing, ms; S is pore surface area, cm^2; V is pore volume, cm^3; ρ_2 is transverse surface relaxation strength of rock, μm/ms.

T_2 relaxation time would be fairly long due to the volume relaxation of light oil in large pores, which is the so-called tailing phenomenon. Natural gas has no volume relaxation. Since it has a large diffusion coefficient, its T_2 relaxation time decreases, which is called the forward shift of T_2 spectrum [12].

Fig. 2 is the oil and gas layers identification plot of Well X1 with NMR. Obvious T_2 spectrum tailing phenomenon can be seen in M and N layers, some signals are more than 1000 ms , so the two layers are identified as oil layers. The T_2 relaxation time of Y and Z layers is basically below 1000 ms, so the two layers are identified as gas layers. NMR can identify oil layers from gas layers clearly, however, NMR is only conducted in key intervals of a small portion of wells due to high cost and long logging time, so it cannot be widely applied.

3.3. Oil and gas layer identification with mud logging

Mud logging is a method to find out underground reservoirs by measuring combustible gas content in mud. The collected gas is fractionated, identified and measured by chromatographic column in chromatographic mud logging technology, and the content of C_1-C_5 can be continuously recorded respectively [13]. Currently, mud logging is mainly applied in identifying oil and gas reservoirs, and the corresponding interpretation methods include chart boards and mathematical statistics. The commonly used chart board methods include Pixler Chart [14], hydrocarbon triangular diagram method [15], hydrocarbon proportion chart board, humidity chart board [13], etc. These chart board methods, using few parameters (only C_1-C_4) but without distinguishing n-paraffins and iso-paraffins, don't make full use of mud logging data.

Conventional mathematical statistic methods include R-factor analysis [16], fuzzy pattern recognition, BP neural network [17], Fisher Linear Discriminant analysis, Mahalanobis distance discriminant analysis [18], and Euclidean distance analysis [19], etc. The common advantage of these mathematical statistic methods is drawing on more data, however, these methods often require a certain amount of samples, and are complex and inconvenient in application. On

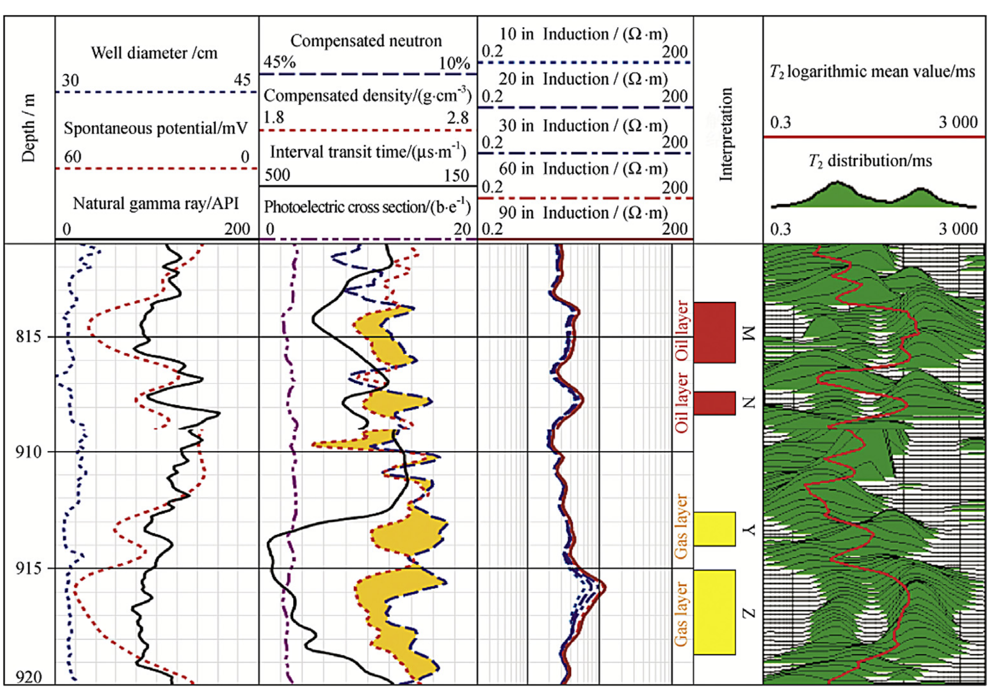

Fig. 2. Oil and gas layer identification plot with NMR (Well X1, 1 in = 25.4 mm).

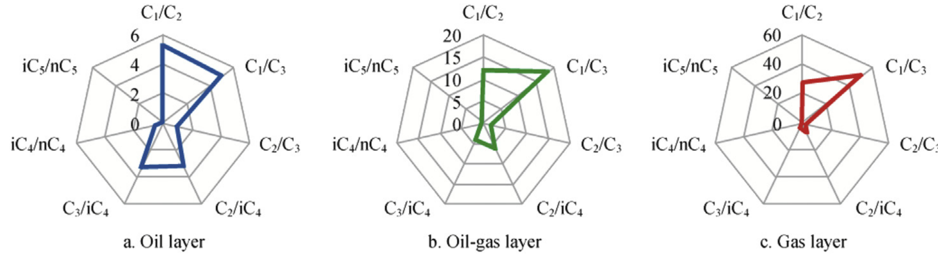

Fig. 3. Oil and gas layers identification with star chart board of gas components.

the whole, both chart boards and mathematical statistics are mainly applied to find oil and gas layers in current mud logging [20], focusing on differentiation of oil and gas layers from water layers rather than differentiation of oil layers from gas layers.

The star chart board of gas components is put forward to identify oil layers from gas layers based on comprehensive comparison of different methods and tests in the Yingdong Oil/Gas Field. Seven ratios, i.e. C_1/C_2, C_1/C_3, C_2/C_3,C_2/iC_4, C_3/iC_4, iC_4/nC_4 and iC_5/nC_5, are used in the star chart board of gas components, which, making full use of mud logging data, can accurately identify oil layers, oil-gas layers and gas layers in the Yingdong Oil/Gas Field. Formation testing and production data have confirmed the coincidence rate of star chart board of gas components hits over 90% (Fig. 3).

4. Quantitative calculation of GOR

There are fewer researches on quantitative calculation of GOR. Gao Chuqiao et al. [21] took condensate gas as a component of formation volume model to establish logging response equation, and established over-determined equation set based on multiple logging curves to get optimal solution of GOR, but he pointed out this method was prone to the effect of mud invasion and needs correcting in application. Li Fangming et al. [22] established the qualitative relationship between “excavation effect of compensated neutron log” and GOR, but the study objects are oil reservoirs in which all produced gas is dissolved gas, therefore, the above-mentioned methods are not applicable to the Yingdong Oil/Gas Field.

Since there are some limitations in telling oil layers from gas layers with logging in the Yingdong Oil/Gas Field, mud logging data which is effective in distinguishing oil layers from gas layers was adopted to calculate GOR by the authors. As is shown in Fig. 4, the total area encircled by sample data points in the star chart of gas components can be divided into two parts: the first part is the quadrangle encircled by C_1/C_2, C_1/C_3, C_2/C_3 and coordinate original point, its area (S_a) is related to the content of light hydrocarbon content; the second part is the heptagon encircled by C_2/C_3, C_2/iC_4, C_3/iC_4, iC_4/nC_4, iC_5/nC_5, C_1/C_2 and coordinate original point, and its area (S_b) is related to heavy hydrocarbon content. In general, $S_a > S_b$. For gas layers, $S_a \gg S_b$, S_b is very small. For oil layers, S_b is relatively large. The S_b area of oil-gas layers falls in between the former two.

After the division of the gas components on star chart, the area ratio S_a/S_b can be calculated with formula (2). Then, a mathematical fitting is performed to establish the relationship between the area ratio and GOR measured by oil and gas test (Fig. 5). They are in power function relationship shown as Formula (4). The larger the area ratio S_a/S_b, the higher the GOR will be.

$$\frac{S_a}{S_b} = \left[\frac{C_1}{C_2}\frac{C_1}{C_3} + \frac{C_1}{C_3}\frac{C_2}{C_3}\right] \Big/ \left[\frac{C_2}{C_3}\frac{C_2}{iC_4} + \frac{C_2}{iC_4}\frac{C_3}{iC_4} + \frac{C_3}{iC_4}\frac{iC_4}{nC_4} + \frac{iC_4}{nC_4}\frac{iC_4}{nC_5} + \frac{iC_5}{nC_5}\frac{C_1}{C_2}\right] \tag{4}$$

where S_a is the quadrangle area related to light hydrocarbon content, dimensionless; S_b is the heptagon area related to heavy hydrocarbon content, dimensionless. C_1 is methane content; C_2 is ethane content; C_3 is propane content; iC_4 is isoparaffin content; nC_4 is n-paraffin content; iC_5 is iso-pentane content; nC_5 is n-pentane content.

$$GOR = 3.044\,5(S_a/S_b)^{4.3005} \tag{5}$$

where, GOR is gas-oil ratio, m^3/m^3.

Fig. 6 is an example of GOR quantitative calculation with mud logging data of Well X2 in the Yingdong Oil/Gas Field. In the interval of 1450–1485 m, the “excavation effect” of conventional logging cannot effectively identify oil layers

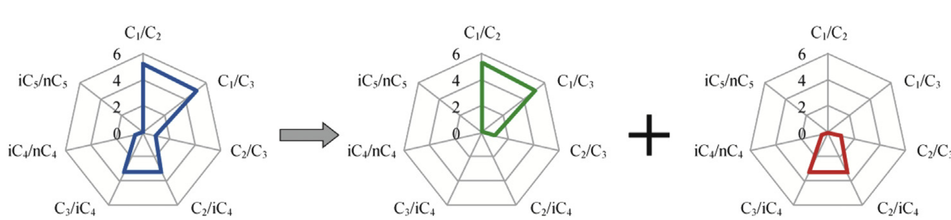

Fig. 4. Schematic of component division in star chart of gas components.

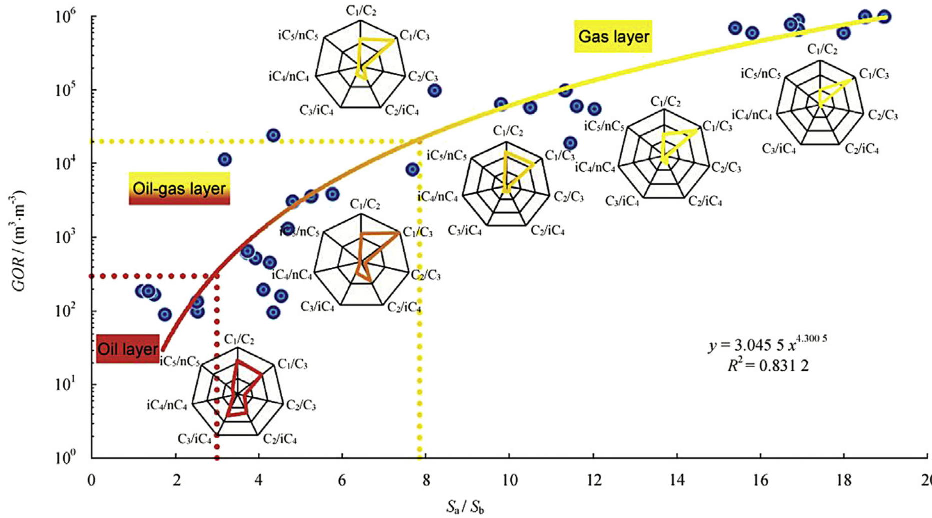

Fig. 5. The relationship between the star chart of gas component area ratio and GOR.

from gas layers, because oil layers and gas layers here have similar "images" on density and compensated neutron logs. When put into production, six layers (A–F) in Well X2 were perforated together, daily flowing production with 5 mm choke was 9.74 m^3/d oil, 9602 m^3/d gas and 0.13 m^3/d water on average. By using the star board of gas components, Layer A, Layer B and Layer C were identified as oil and oil-gas layers with the corresponding GOR of 36 m^3/m^3, 2000 m^3/m^3 and 180 m^3/m^3 respectively; Layer D, Layer E and Layer F were identified as gas layers, with the corresponding GOR of 48 000 m^3/m^3, 27 000 m^3/m^3 and 37 000 m^3/m^3 respectively. The identification results are consistent with that of ultrasonic three-phase production profile test.

5. Conclusions

(1) Conventional well logging cannot accurately identify oil and gas layers due to the influence of formation pressure, hydrogen index, shale content, borehole conditions, mud invasion and other factors. NMR is effective in

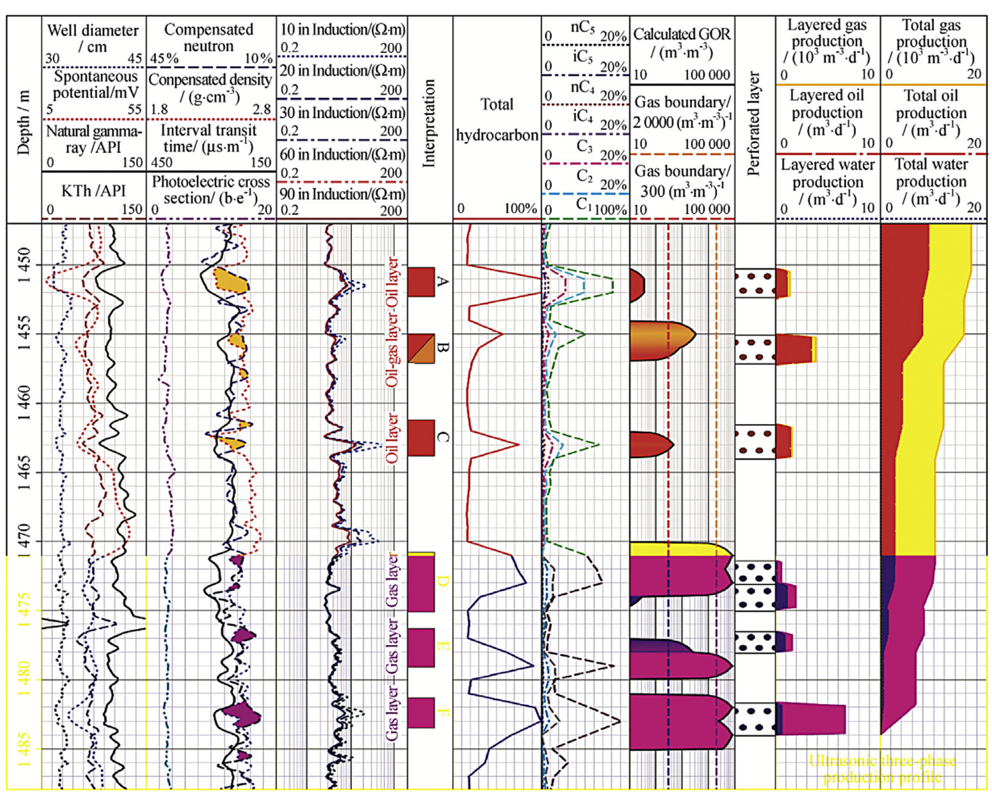

Fig. 6. An example of GOR quantitative calculation with mud logging of Well X2.

distinguishing oil and gas layers but cannot be widely applied due to high cost. The star chart of gas components is the best choice to identify oil and gas layers.

(2) Area S_a in the star chart of gas components is related to light hydrocarbon content, the area S_b is related to heavy hydrocarbon components, and there is a good correlation between the area ratio S_a/S_b and GOR, the bigger the area ratio S_a/S_b, the higher the GOR will be.

(3) Actual field data demonstrates that the oil and gas layers identification and GOR quantitative calculation based on mud logging are suitable for the Yingdong Oil/Gas Field.

References

[1] Ping Sun, Zeqing Guo, Weihong Liu. Accumulation mechanism of the yingdong I field in the Qaidam Basin, NW China. Petrol Explor Dev 2013;40(4):429−35.

[2] Huanxu Zhang, Shijia Chen, Jing Zhang, Peng Wang, You Zhou, Yinghai Jiang. Large fault throw fault sealing ability evaluation-An example from Youshashan fault in Yingdong area of Qaidam Basin. Xinjiang Pet Geol 2013;34(4):421−3.

[3] Kui Deng, Wenping Xu, Yaping Li, Yanhai Song. Logging identification of oil/gas layers in N22-N1 in the Nanbaxian Oil and Gas Field. Nat Gas Ind 2009;29(7):12−5.

[4] Guijie Li, Jianmin Zhang, Aizhong Yue, Song Linghu, Biao He. Effect of gas in the sand-mudstone layer on compensated neutron log. Well Logging Technol 2005;29(6):515−27.

[5] Yun Zhang, Xiaohong Zhu, Yangbing Li, Jianmeng Wu, Xiang Ge. Log evaluation of tight clastic reservoirs in the deep of western Sichuan Basin. Nat Gas Ind 2010;30(1):31−5.

[6] Zhaohui Zhang, Chuqiao Gao, Yongde Gao. Theoretical simulation and analysis factors of resistivity in vuggy reservoir. J Southwest Petroleum Univ: Sci Technol Ed 2014;36(2):79−84.

[7] Liangxiao Zhao, Huimin Xing. A new parameter for gas reservoir appraisal: suffusive degree. Nat Gas Ind 2010;30(6):31−4.

[8] Zhengming Yang, Chenxu Bian, Xiangui Liu, Xuewu Wang. Study on waterflooding production of typical low permeability reservoirs. J Southwest Petroleum Univ: Sci Technol Ed 2013;35(6):83−9.

[9] Yawu Hu, Jia Yang, Yongjun Wang, Li Luo. Application of NMR to the evaluation of low-porosity and low-permeability Upper Triassic reservoirs in the central Sichuan Basin. Nat Gas Ind 2012;32(3):45−8.

[10] Fan Liu, Hanqiao Jiang, Xiansong Zhang, Junjian Li. Study on the mechanism of horizontal well development based on NMR. J Southwest Petroleum Univ: Sci Technol Ed 2013;35(6):99−103.

[11] Yudan He, Zhiqiang Mao, Lizhi Xiao, Yuanzhong Zhang. A new method to obtain capillary pressure curve using NMR T2 distribution. J Jilin Univ: Earth Sci Ed 2005;35(2):177−81.

[12] Pengju Li, Zhipeng Zhang, Dapeng Jiang. Review of fluid identification methods with NMR logging. Well Logging Technol 2011;35(5): 396−401.

[13] Liping Yang, Jin Yang. Modern comprehensive logging technology base and application. Beijing: Petroleum Industry Press; 2010. p. 93−7.

[14] Mingfa Yu, Huanling Bian, Wei Zhuang, Dawei Zhu, Xingshu Ye, Zong'an Xue. Applicability analysis for Pixler Chart interpretation method of gas logging. Mud Logging Eng 2013;24(1):14−9.

[15] Ruihong Wang, Xingli Li, Yunjiang Cui, Hongwei Yangh. Application of gas logging technology in fluid identification of uncertain layers of Bohai. Petrol Geol Eng 2013;27(1):72−5.

[16] Chengbo Lian, Jianhua Zhong, Hanlin Li, Yongjun Zhao, Fulong Cai, Juntao Zhang. Extraction of gas logging information and identification of oil-bearing reservoirs. Acta Geol Sin 2007;81(10):1439−43.

[17] Hanlin Li, Chengbo Lian, Shikun Ma, Minyan Liu. Identification method of oil bearing reservoirs based on gas logging data. J China Univ Petrol: Nat Sci Ed 2006;30(4):21−3.

[18] Shuyuan Zhang, Jianwei Zhao, Anran Geng, Peng Zhang, Hengshen Yao. Two methods to identify the formation fluid property by using gas logging data. J Oil Gas Technol 2010;32(1):278−81.

[19] Yangqing Wei, Feilong Wei, Haoyang He, Feng Liu, Jun Jiang. A new method for the mud logging identification of reservoir fluids: a case study from the Xujiahe reservoirs in the western Sichuan Basin. Nat Gas Ind 2013;33(7):43−6.

[20] Xie Tang, Jiaqqiong Tang, Yuhai Luo, Yuerui Deng, Jian Cui. MWD analysis of thin carbonate reservoirs in horizontal wells. Nat Gas Ind 2013;33(9):43−7.

[21] Chuqiao Gao, Chengguang Zhang, Chengwen Xiao. Identifying condensate gas-oil ratio from well logging. Oil Geophys Prospect 2003;38(3):290−3.

[22] Fangmin Li, Zhongyuan Tian, Aming Jiang, Xiaxia Wang. Prediction of reservoir depletion degree and production GOR using logging-while-drilling data. Petrol Explor Dev 2009;36(5):617−22.