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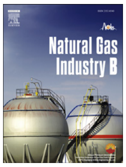

Research article

Logging identification of the Longmaxi mud shale reservoir in the Jiaoshiba area, Sichuan Basin

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Abstract

Compared with conventional gas reservoirs, shale gas reservoirs are not sensitive to petrophysical properties, making it much difficult to identify this kind of reservoirs with well logging technologies. Therefore, through a comparison of the logging curves of the Lower Silurian Longmaxi marine shale in the Jiaoshiba area, Sichuan Basin, it is found that the mud shale on conventional log curves generally features high gamma ray, high uranium, low thorium, low kalium, relative high resistivity, high interval transit time, low neutron, low density and low photoelectric absorption cross section index, while on elements logging curves, it features an increase of silicon content and a decrease of aluminum and iron content. Based on the logging response characteristics of mud shale, the logging curves most sensitive to shale, gamma ray, neutron and density logging were selected and overlaid to identify mud shale effectively. On the basis of qualitative identification, the density logging value can identify the non-organic-rich mud shale from organic-rich mud shale, because the former has a density of 2.61–2.70 g/cm^3, while the latter has a density of less than 2.61 g/cm^3. The identification results agree well with the results of field gas content test, *TOC* experiment, and gas logging, so this study can provide reference for the logging interpretation.

Keywords: Sichuan Basin; Jiaoshiba area; Silurian; Mud shale; Shale gas; Logging response; Reservoir identification; Overlay technique; Intersection method

Shale gas is a natural gas occurred and enriched in multiple phase states in mud shale which is mostly kerogenetic or organic-rich dark black mud shale and high-carbon mud shale, occasionally intercalated by silty mudstone, argillaceous siltstone and siltstone [1–4]. Most shale gas occurs in fractures, pores and other reservoir space in a free state, and some on kerogen, clay grain and pore surfaces in an adsorption state, and a very small part in kerogen and siltstone interlayers in a dissolved state [5]. The occurrence modes of shale gas forces us to explore the log response characteristics of such kind of gas reservoirs. Compared with conventional gas reservoirs, shale gas ones feature weakly sensitive geophysical parameters, which largely increases the difficulty of using geophysical well logging techniques to identify shale gas [6,7].

Wu Qinghong et al. thought that shale reservoirs feature "4 highs and 2 lows", and they used a combination method of gamma ray (GR), resistivity, neutron porosity, interval transit time and induction electrical log (IEL) to identify shale gas reservoirs [8]. Lewis et al. used a combination of GR, resistivity, density (DEN) and litho-density log (LDL) to find out the typical logs of gas-bearing shale [9]. Cluff et al. sorted out the shale gas reservoirs of Woodford Fm in the Arkoma Basin with natural gamma ray spectrometry log (SGR) [10]. Bowman et al. studied the shale beds of Barnett Fm in Fort Worth Basin, Mississippi, and considered that the intersection of acoustic logging and resistivity logging was capable of discriminating the lithology [11]. Only by sufficiently understanding the log response characteristics of the mud shale, can we effectively identify mud shale reservoirs, and then conduct

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calculation and study on mud shale reservoir parameters. This paper, on the basis of studying the well logging evaluation of shale gas at home and abroad, analyzes the actual shale gas well data, sums up the log response characteristics of marine mud shale formation in Jiaoshiba area, Fuling district, Chongqing city, explores the approach suitable for recognizing the mud shale reservoirs in this area, in the hope to better evaluate log parameters.

1. Log response characteristics of mud shale

Jiaoshiba is located in Fuling district, Chongqing city, and tectonically in the Baoluan-Jiaoshiba anticlinal zone of the highly steep fold belt in the eastern Sichuan Basin. Lower Silurian Longmaxi Fm. is the primary target of Lower Paleozoic marine shale gas in the Sichuan Basin and its peripheral areas. The buried depth of marine shale gas reservoirs in Jiaoshiba area ranges from 2300 m to 2595 m in exploration wells JY1, JY2HF, JY3HF and JY4HF. Experimental analyses show that mud shale from Well JY1 mainly consists of gray black mudstone, black carbargillite, gray black carbargillite, gray black silty mudstone, gray black shale and dawk. The mud shale has a porosity of 1.17%–7.22%, 4.52% on average, a permeability of 0.001 6–335.209 mD, 28.309 mD on average, a *TOC* of 0.55%–5.89%, 2.54% on average, a total gas concentration of 1.18–5.75 m^3/t, 3.14 m^3/t on average, a vitrinite reflectance (R_o) of more than 2%, and a brittle mineral content of 33.9%–80.3%, 56.5% on average. The brittle mineral is dominantly quartz, which accounts for 37.3% on average.

1.1. Response characteristics of GR logs

Gamma ray log (GRL) reflects the resultant intensity of natural gamma rays sent out by rocks. Clay in a mud shale formation makes a big contribution to the radiation property, and different clay minerals have different contribution ratios. Montmorillonite is free of radioactive matter itself, but with a stronger cation exchange capacity and larger surface, it has strong absorptivity to radioactive matters and contains lots of urania. Therefore, it makes the maximum contribution to the radiation of clay; illite, containing kalium itself, is radioactive, and has certain absorptivity to urania; chlorite is free of radioactivity itself, besides poor in cation exchange capacity, it lacks radioactive attachment. Total rock X-ray diffraction of 87 samples taken from the major gas-bearing mud shale interval of Wufeng Fm. – Longmaxi Fm. Member I in Well JY1 (2330.46–2414.88 m well depth), indicates that the clay mineral content has a drop trend from the top downward, as is shown in Fig. 1 (left), and the clay content ranges from 16.6% to 62.8%, 40.9% on average. The X-ray diffraction also shows that the clay mineral is dominantly illite-montmorillonite mixed layer, with a content of 25.0%–85.0%, 54.5% on average; followed by illite, with a content of 12.0%–68.0%, 39.5% on average; and minor chlorite, with a content of 1.0%–20.0%, 6.0% on average, as is shown in Fig. 1 (right). Fig. 2 shows the comparison of GR logs of Wufeng Fm. – Longmaxi Fm. Member I mud shale in Wells JY1, JY2HF, JY3HF and JY4HF. The curves are basically the same in shape, and the log values have a gradually increasing trend from top to bottom, which shows that the clay mineral

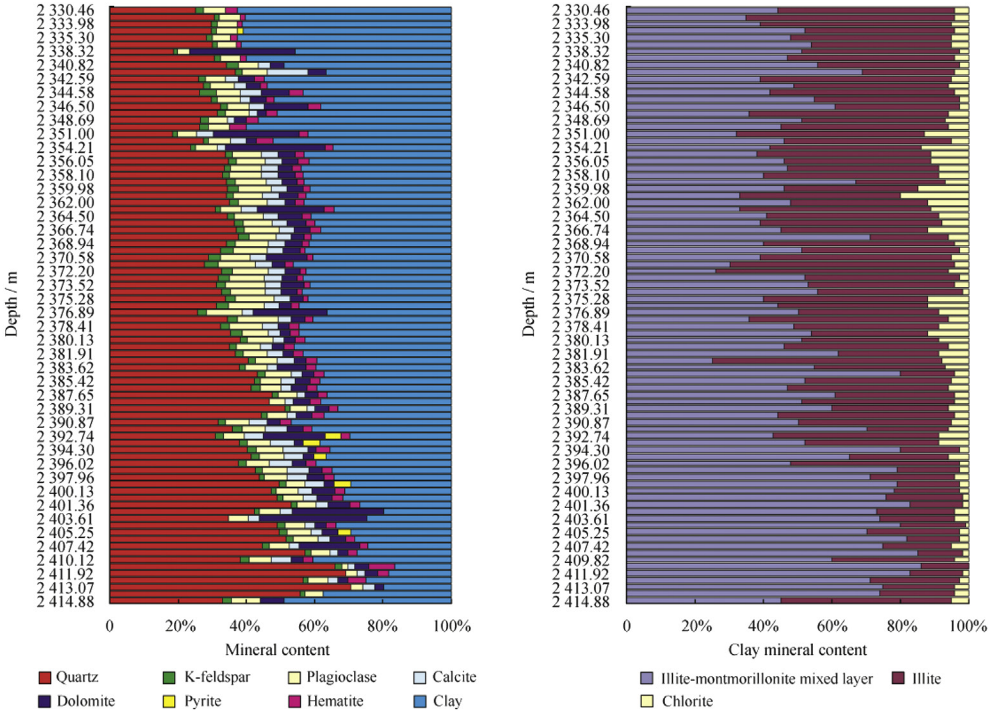

Fig. 1. Total rock mineral content analysis diagram.

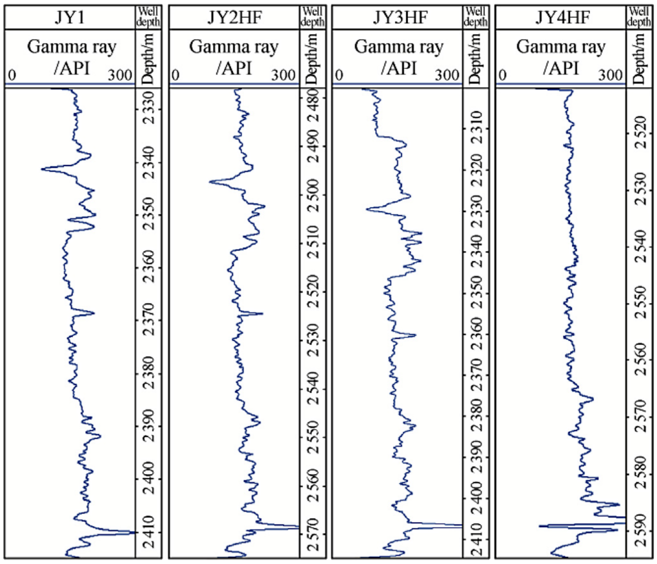

Fig. 2. GR logs of mud shale.

composition and content of Wells JY2HF, JY3HF and JY4HF are very similar to those of Well JY1.

1.2. Response characteristics of SGR logs

Natural gamma ray spectrometry log (SGR) reflects the uranium, thorium and kalium content in rocks and the resultant gamma ray. SGR can provide more detailed gamma ray information. As is shown in Fig. 3, the kalium and thorium content is high but the uranium content is low (relative to kalium and thorium) in the upper claystone; while in the lower claystone, with the increase of organic content, the adsorption of clay grain to uranium ion gets stronger, so the uranium content in clay goes up significantly. The uranium, thorium and kalium curves of the four wells are basically the same in shape; overall, the uranium content gradually increases but the thorium and kalium content gradually decreases from top to bottom.

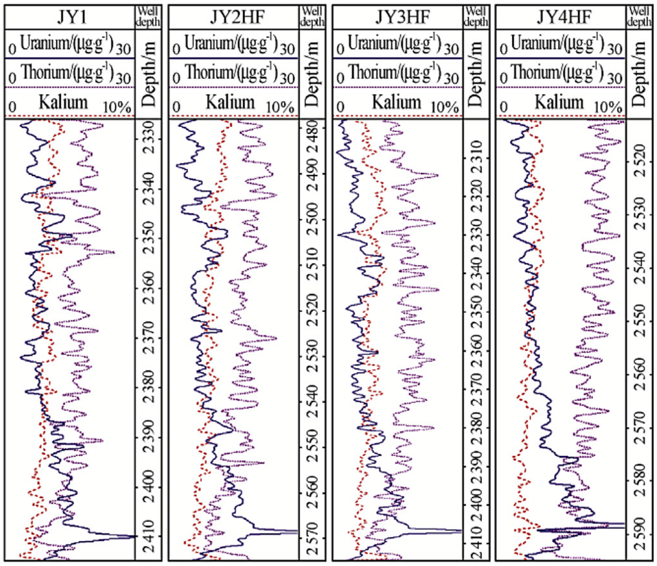

Fig. 3. SGR logs of mud shale.

1.3. Response characteristics of resistivity logs

The change in resistivity logs is the result of a combined effect of various factors, reflecting the changes in rock mineral composition, hydrothermal alteration, cavity and fracture development level, fluid property and hydrocarbon content. Because the mineral constituents of mud shale are complex, when the content and structure of mineral constituents change, the rock resistivity also changes. The property of fluid in the pores also has a larger effect on the rock resistivity. When the reticular fracture developed is filled with drilling filtrate, the logging resistivity can also decrease. In addition, the weathering of feldspar into kaolinite, and the alteration of biotite into chlorite, can also lower the rock resistivity. The organic matter maturity also has an effect on the resistivity. As is shown in Fig. 4, the shape of resistivity logs are basically the same, and the resistivity of mud shale interval is lower on the whole, but the resistivity of upper mud shale is lower than that of lower mud shale, which is related to the increase of organic matter content in the lower mud shale.

1.4. Response characteristics of tri-porosity logs

1.4.1. Response characteristics of acoustic logs

The acoustic logs exhibit different features due to the effects of rock mineral composition, rock tightness degree, rock texture and porous fluid property, etc. Fig. 5 shows the tri-porosity logs, in which the acoustic logs are similar in shape, and interval transit time has an increase tendency from top to bottom. The increase of organic content could increase the porosity of reservoirs, and thus resulting in the increase of SDT value.

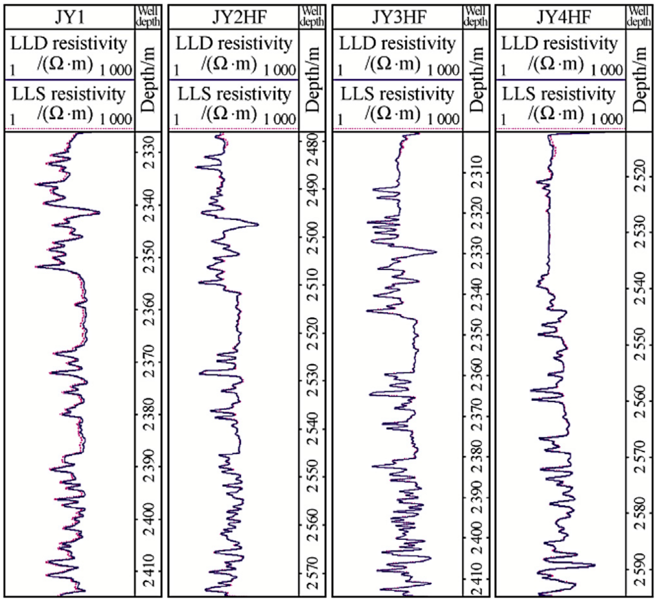

Fig. 4. Resistivity logs of mud shale.

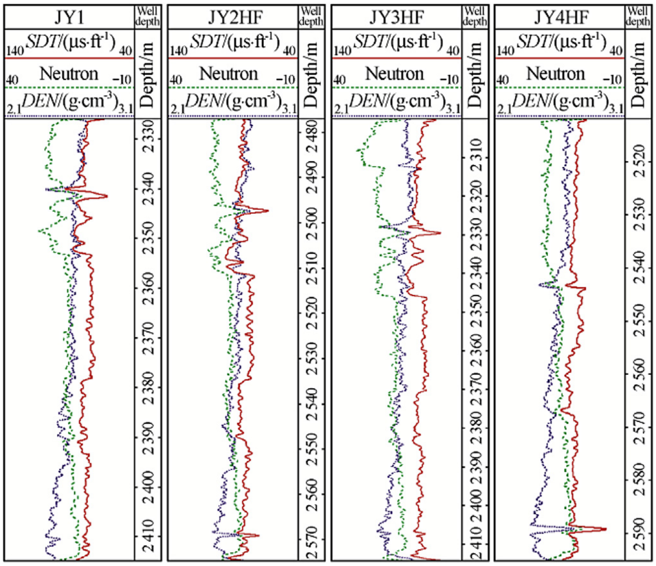

Fig. 5. Tri-porosity logs of mud shale. 1 ft = 0.3048 m.

1.4.2. Response characteristics of neutron logs

Neutron logs are strongly affected by formation lithology and fluid property, and change with the change of fluid content in pores and cracks. When the rocks are altered, secondary minerals like chlorite and sericite containing substantial crystal water and textural water, frequently lead to high neutron porosity. As is shown in Fig. 5, the neutron logs are similar in shape, and the neutron log values have a decline tendency from top to bottom.

1.4.3. Response characteristics of density logs

Density logs are affected by rock mineral components, pores, cracks, the boreholes and mud cakes. Because the density of organic matter is lower, the increase of organic matter content in the mud shale would cause the drop of density (Fig. 5); the density logs have similar shape, and the density log values exhibit a decrease tendency from top to bottom.

1.5. Response characteristics of PE logs

Photoelectric absorption cross section index (PE) of rocks can be obtained from lithology-density logs, which can better discriminate lithology. The PE values of different minerals are largely different, but PE of fluids is very small; the influence of fluid property and content in rocks on PE is very small, therefore, the PE value depends mainly on the mineral composition and the content of rocks. As is shown in Fig. 6, the PE logs have similar shape, and the PE values exhibit a decline tendency from top to bottom. The total rock X-ray diffraction analysis of Well JY1 shows that the quartz content rises gradually from top to bottom of Wufeng Fm. − Longmaxi Fm. Member I mud shale, and the quartz content is a great part in the whole experimental analysis interval (2330.46−2414.88 m), reaching 70.6% at maximum, and since the PE value of quartz is lower, the PE value of the section would be smaller.

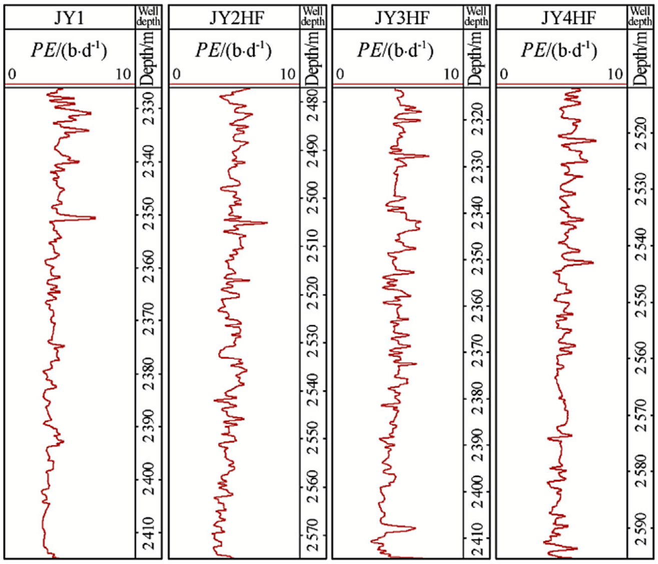

Fig. 6. PE logs of mud shale.

1.6. Response characteristics of ECS logs

ECS log response is primarily the overall reflection of percentage of various elements in rock minerals, mainly including Si, Al, Ca, Fe, Gd, S and Ti in practical application [12]. Among them, Si can indicate quartz, Ca is closely related to calcite and dolomite, Al and Si can indicate feldspar, S and Ca can be taken as the indicator element of gypsum, Fe is related to pyrite and hematite, and Al is related to clay content. Fig. 7 shows the ECS logs of the mud shale, the tracks are Si, depth, Al, Ca, Fe, Gd, S and Ti from left to right in turn. On the whole, Si content increases but Al and Fe content decrease gradually from top to bottom, consistent with mineral composition from bulk-rock analysis; Ca, Gd and Ti content does not show any regular variation pattern overall; and S content approaches zero locally.

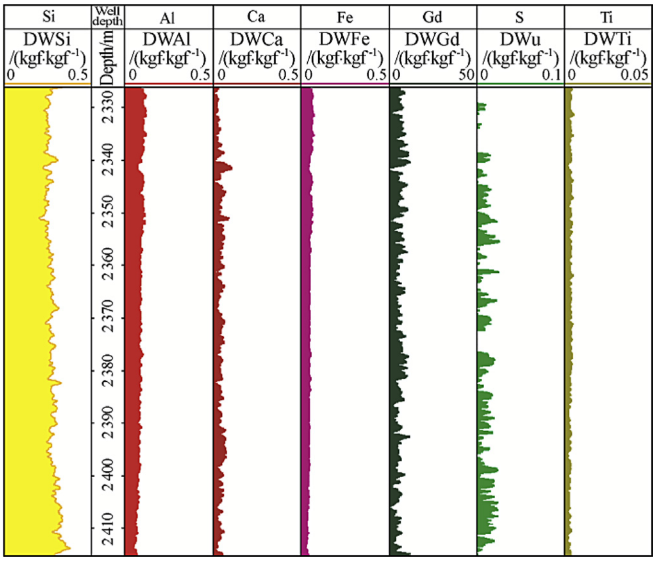

Fig. 7. ECS logs of mud shale.

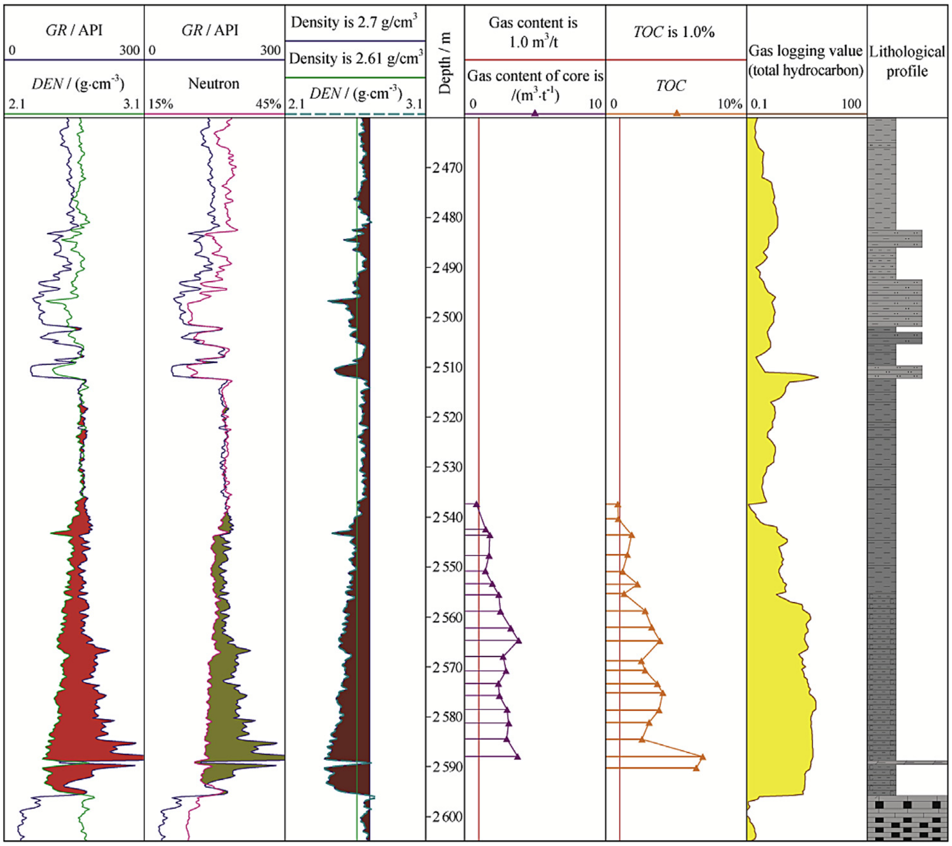

Fig. 8. Logging identification of mud shale reservoir in Well JY4.

2. Recognition of mud shale reservoirs by logging technique

2.1. Overlay logs

Conventional logging suite can be used to identify mud shale. Based on the analyses of log response characteristics above, GR, DEN and neutron logs sensitive to mud shale were selected to recognize the lithology and mark off the organic-rich mud shale intervals.

GR log indicating the shale content of formation can be used to satisfactorily discriminate sandstone, mudstone and limestone; therefore, it can be taken as the base curve. GR log was superimposed with DEN and neutron logs that are relatively sensitive to mud shale, and gray black mudstone was selected as the reference lithology. As is shown in Fig. 8, the mudstone in the lower part of dark gray siltstone at 2509.63–2512.25 m well depth was taken as the reference lithology, the log scale was adjusted to make the superimposed logs coincide here. The first and second tracks represent GR-DEN and GR-neutron logs superimposed tracks respectively. In the upper siltstone interval and the lower limestone interval, the spacing amplitude of these two logs is relatively large, and the DEN and neutron logs incline to the right of the base curve, which is called "negative variance"; in the hole interval of 2512.25–2595.7 m, the upper logs basically coincide, but the lower logs have a large spacing amplitude, and the DEN and neutron logs incline to the left of the base curve, which is called "positive variance". The coincident interval at upper logs is defined as non-organic-rich mud shale interval, and the "positive variance" interval at lower logs is defined as organic-rich mud shale interval. The organic-rich mud shale interval recognized by GR-DEN overlay logs is at a well depth of 2536.0–2595.7 m, with a thickness of 59.7 m; and that by GR-neutron overlay logs is at a well depth of 2538.7–2595.7 m, with a thickness of 57.0 m. The fifth track is the measured total gas content, the sixth is the analyzed *TOC*, and the seventh is the total hydrocarbon of mud logging from left to right. The gas content, *TOC* and total hydrocarbon corresponded by the recognized organic-rich mud shale interval are all higher, and on the whole, the mud shale interval with large "positive variance" has higher gas content, *TOC* and total hydrocarbon values.

2.2. Crossplots

GR logs and tri-porosity logs sensitive to mud shale were selected to conduct crossplot analysis. Because the density of kerogen is lower, the increase in organic matter content in the mud shale can reduce its density, meanwhile, when the organic matter increases, the reservoir porosity would increase, thus resulting in the decrease of density. Fig. 9 shows the crossplot of *TOC* from experimental test and log density value. The 222 sample points in Fig. 9 are the experimentally

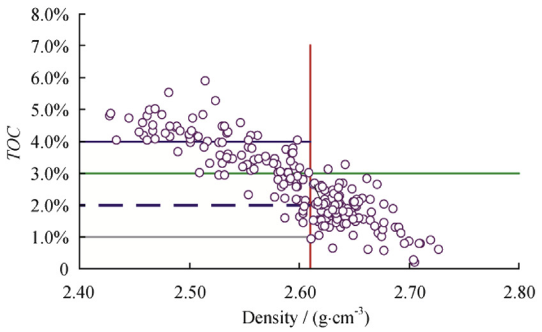

Fig. 9. Crossplot of *TOC* and log density value from experimental analysis.

analyzed data of Well JY1 and JY2HF. The red line in the figure stands for 2.61 g/cm^3 density value, The data points at the left of the red line all have a *TOC* of more than 1%; apart from individual data points, the *TOC* of other data points is all no less than 2%, that of the overwhelming majority of data points is higher than or equal to 3%, and that of some data points is even higher than or equal to 4%; according to the industrial standard, the shale gas reservoirs corresponded by the data points at the left of the red line are high-ultrahigh shale gas reservoirs. The data points at the right of the red line all have a *TOC* of less than 3%, mostly below 2%, and some even less than 1%. The density value corresponded by the organic carbon data points in Fig. 9 is basically less than 2.70 g/cm^3. Therefore, the density value of 2.61 g/cm^3 can be taken as the division criterion of organic-rich mud shale interval, and 2.70 g/cm^3 as that of mud shale interval. On the basis of qualitative − semi-quantitative recognition of mud shale reservoirs using the aforesaid overlay logs, quantitative recognition is further conducted on them. As is shown by the third track in Fig. 8, the organic-rich mud shale interval with log density of less than 2.61 g/cm^3 is at a well depth of 2539.6−2595.7 m, with a thickness of 56.1 m; whereas the non-organic-rich mud shale interval with a log density of 2.61−2.70 g/cm^3 is at a well depth of 2512.25−2539.6 m. The organic-rich mud shale interval marked off by density log value also matches well with the field measured gas content, *TOC* from experiment and gas logging value of mud logging. Also as is shown in the third track, an interval with log density of less than 2.61 g/cm^3 and another interval with a density of less than 2.70 g/cm^3 can be seen in the upper and lower parts of 2512.25−2595.7 m interval respectively, indicating that the mud shale and organic-rich mud shale cannot be identified by density log alone, and other methods have to be combined with it to do the job.

The eighth track in Fig. 8 shows the mud logging lithology. It can be seen from this track that 2482.5−2486.0 m and 2492.48−2501.92 m intervals are dark gray argillaceous siltstone; 2509.63−2512.25 m interval is dark gray siltstone; 2512.25−2595.78 m interval is mud shale, the lithology is mainly gray black mudstone, gray black silt-bearing mudstone, gray black carbargilite, and a little dark gray argillaceous dolomite locally; while 2595.78−2610.50 m interval is limestone, including gray dolomite-bearing limestone and gray knollenkalk. The lithology was classified into siltstone, mud shale and limestone in logging identification, and the log values corresponded by them are extracted to conduct crossplot analysis and find out the identification effect.

Fig. 10(a) and (b) shows the GR-neutron and GR-DEN crossplots respectively. It can be seen from these Figures that GR can clearly tell mud shale from siltstone and limestone. The GR value of mud shale is generally higher than 150 API; and the GR value of siltstone is higher than that of limestone. On the whole, the neutron value of mud shale is higher than that of limestone and siltstone, whereas the density value of mud shale is lower than that of limestone and siltstone, but any one log alone cannot identify mud shale accurately. On the basis of mud shale identification, the non-organic-rich mud shale and organic-rich mud shale are further identified. Non-organic-rich mud shale and organic-

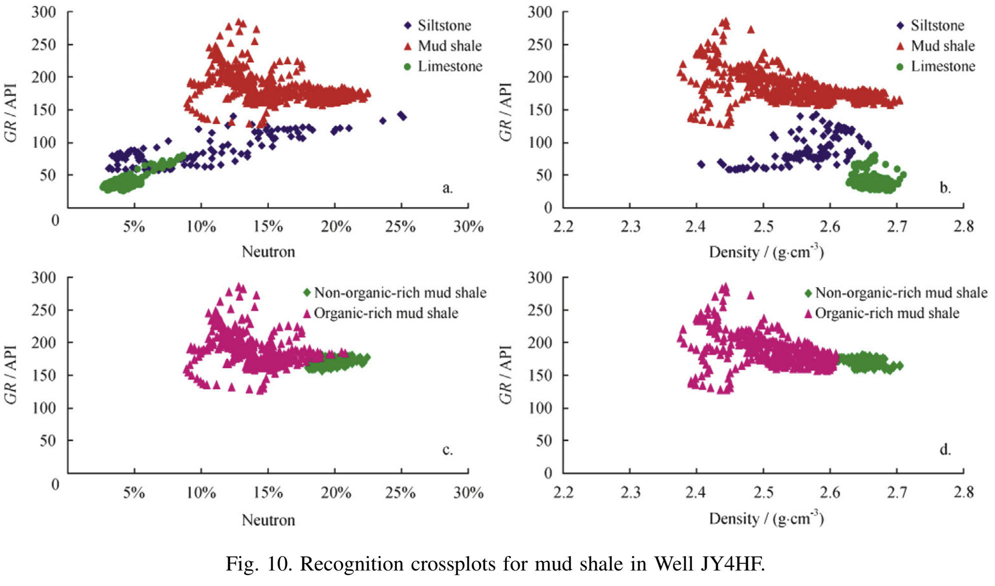

Fig. 10. Recognition crossplots for mud shale in Well JY4HF.

rich mud shale are discriminated based on the experimental *TOC* values of 19 samples taken from Well JY4HF; the interval with the *TOC* of more than one is classified as organic-rich mud shale interval, which, at a well depth of 2540.34–2595.7 m, is 55.36 m thick; whereas the interval of 2512.25–2540.34 m is identified as non-organic-rich interval. Fig. 10(c) and (d) shows the GR-neutron and GR-DEN crossplots of mud shale interval respectively. It can be seen from these Figures that the density log can best discriminate the non-organic-rich mud shale and organic-rich mud shale, followed by neutron log, while GR value can hardly discriminate them.

3. Conclusions

1) The Jiaoshiba marine mud shale reservoir, stable in distribution, has distinct log response characteristics; it features “4 highs and 5 lows”, i.e., high GR, relatively high resistivity, high SDT, high uranium, low neutron, low density, low PE, low thorium, and low kalium on conventional logging curves; meanwhile, it exhibits an increase of silicon content and a decrease of aluminum and ferrum content on unconventional elemental log.
2) The superimposition of GR log and DEN (or neutron) log can better sort out mud shale reservoirs, and effectively discriminate the organic-rich mud shale and non-organic-rich mud shale. The density log is fairly sensitive to mud shale reservoirs, and density logs can identify the organic-rich mud shale reservoirs on the basis of qualitative – semi-quantitative identification; the log density of organic-rich mud shale is less than 2.61 g/cm^3, while that of non-organic-rich mud shale ranges in between 2.61 g/cm^3 and 2.70 g/cm^3.
3) The research results can provide basis for the calculation of log parameters of shale gas in this area.

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References

[1] Wang Shejiao, Wang Lansheng, Huang Jinliang, Li Xinjing, Li Denghua. Accumulation conditions of shale gas reservoirs in Silurian of the Upper Yangtze region. Nat Gas Ind 2009;29(5):45–50.
[2] Zhang Jinchuan, Xue Hui, Zhang Deming, Pu Jun. Shale gas and reservoiring mechanism. Geoscience 2003;17(4):466.
[3] Law BE, Curtis JB. Introduction to unconventional petroleum systems. AAPG Bull 2002;86(11):1851–2.
[4] Mosheni P. Gothic and Hovenweep shale play opportunity on the Ute Mountain Ute Indian Reservation, Colorado. Michigan: Indian Mineral Development Act; 2010.
[5] Nie Haikuan, Zhang Jinchuan. Shale gas reservoir distribution geological law, characteristics and suggestions. J Central South Univ Sci Technol 2010;41(2):700–8.
[6] Luo Rong, Li Qing. Log evaluation, seismic prediction and monitoring techniques of shale gas reservoirs. Nat Gas Ind 2011;31(4):34–9.
[7] Zhang Jinchuan, Xu Bo, Nie Haikuan, Deng Feiyong. Two essential gas accumulations for natural gas exploration in China. Nat Gas Ind 2007;27(11):1–6.
[8] Liu Shuanglian, Lu Huangsheng, Feiyong Deng. Evaluation methods and characteristics of log evaluation technology in shale gas. Well Logging Technol 2011;35(2):112–6.
[9] Lewis R, Ingraham M, Williamson J, Sawyer W, Frantz J. New evaluation techniques for gas shale reservoirs. In: SPWLA 47th annual logging symposium. Houston: Society of Petrophysicists and Well-Log Analysts; 2004.
[10] Cliff B, Miller M. Log evaluation of gas shales: a 35-year perspective. In: SPWLA 52nd annual logging symposium. Houston: Society of Petrophysicists and Well-Log Analysts; 2010.
[11] Liu Xugang, Sun Jianmeng, Guo Yunfeng. Application of elemental capture spectroscopy to reservoir evaluation. Well Logging Technol 2005;29(3):236–40.
[12] Pan Renfang, Zhao Mingqing, Wu Yuan. Application of log evaluation technology in shale gas. China Sci Technol Inf 2010;(7):16–8.