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Evaluation of Shale Reservoir Quality by Geophysical Logging for Shuijingtuo Formation of Lower Cambrian in Yichang Area, Central Yangtze

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ABSTRACT: Taking the shale of Shuijingtuo Formation of Lower Cambrian in Yichang area as the research object, the shale reservoir characteristics are comprehensively evaluated and classified by fitting regression and formula calculation method in this study, using laboratory testing and geophysical logging data. The results show that the interpretation data of ECS (elemental capture spectroscopy) logging has a high correlation with the measured minerals data, which can be a good method to evaluate the minerals component of the shale. The calculated content of brittle minerals at the lower part of Shuijingtuo Formation is the relatively highest, generally more than 40%, which is the most favorable segment for fracturing. The correlation coefficient between the interpretation data of CMR (combinable nuclear magnetic resonance) logging and the result of laboratory porosity test is 0.97, which can effectively and accurately evaluate the reservoir porosity. The evaluation results show that the porosity of the lower member of Shuijingtuo Formation is generally greater than 3%, while that of the upper member is generally less than 3%. The lower segment is with the relative optimal physical conditions. There is a good correlation between the acoustic logging data and the gas bearing content testing results. A gas bearing content evaluation model is established. The results show that the gas bearing content of the lower 20 m shale is generally more than 2%, indicating that the lower part is a shale gas enrichment segment. Mechanical parameters such as Young modulus, Poisson ratio and brittleness index of shale reservoir are evaluated by using the logging data of P-wave time difference and S-wave time difference. The continuous 15 m shale at the lower part is with the relatively optimal low Poisson ratio, high Young modulus and high brittleness index, developing the optimum brittle condition. Based on the evaluation and classification of above parameters, the shale is divided into three types. The Type Ⅰ is the optimal, mainly located at the bottom. Its thickness is 8.5 m in total. The Type Ⅱ mainly develops at the middle part. The Type Ⅲ is the worst, mainly at the upper part.
KEY WORDS: reservoir evaluation, shale, Shuijingtuo Formation, Lower Cambrian, Yichang area.

0 INTRODUCTION

In recent years, important breakthroughs have been made in shale gas exploration of the Lower Cambrian Shuijingtuo Formation in Yichang area, which has confirmed the great shale gas potential in this area (Luo et al., 2019; Chen et al., 2017a; Zhai et al., 2017). The shale is with high organic matter abundance, good organic matter type, high degree of thermal evolution, large thickness and good gas bearing property (Chen et al., 2018; Tang et al., 2017; Liu et al., 2015). However, due to the development of remarkable reservoir heterogeneity, there is differential enrichment of shale gas in the reservoir. As the systematic reservoir evaluation and dessert prediction of the shale had not yet been conducted in this area, it is lack of better understanding of the reservoir quality (Wei et al., 2020; Chen et al., 2017b). It is of great significance for us to reveal the mechanism of the shale gas occurrence and enrichment and resource potential by using the laboratory testing and the geophysical logging data to carry out the comprehensive reservoir evaluation and favorable reservoir optimization. Generally, shale reservoir evaluation includes

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geological analysis, sample testing, geophysical logging, and seismic evaluation (Jiang et al., 2019; Liu et al., 2019; Rui et al., 2017; Clarkson et al., 2012; Hampson et al., 2001). Geophysical logging evaluation is one of the important methods for shale reservoir evaluation (Jin et al., 2015; Holt et al., 1996). It can reveal reservoir parameters accurately and efficiently by combining with laboratory testing results (Dadashpour et al., 2008). It is widely used in reservoir evaluation in exploration stage. At present, conventional logging data (natural gamma, resistivity, neutron, density, acoustic, etc.) and special logging data (nuclear magnetic resonance, dipole acoustic wave, element capture spectroscopy, etc.) are mostly used to evaluate unconventional oil and gas reservoirs at domestic and overseas, and corresponding evaluation methods are established (Nabawy and El Sharawy, 2018; Han et al., 2016; Li et al., 2011). Systematic evaluation of the shale was carried out (Schmoker et al., 1981). It was thought that TOC (total organic carbon content) had a good linear relationship with density logging and natural gamma log, and the above two logging curves could be used to evaluate the TOC of the shale. Resistivity, neutron, density, acoustic logging data and fuzzy logic techniques were also used to establish a neural network and calculate the TOC (Khoshnoodkia et al., 2011). A multi-mineral volume model was also established to evaluate the mineral composition, porosity, TOC and other parameters of the reservoir by using logging data (Qian and Yu, 2013). Rock mechanical parameters were also evaluated by using well logging data (Onalo et al., 2018). Previous studies have shown that parameters such as reservoir characteristics, source rock characteristics and mechanical properties are important aspects of shale reservoir evaluation (Zargari et al., 2013; Chen et al., 2011; Lucier et al., 2011). Reservoir quality were mainly comprehensively analyzed and evaluated through the geophysical model construction of reservoir parameters (Tan et al., 2010). Therefore, this study intends to systematically reveal the quality characteristics of the shale reservoir of Shuijingtuo Formation in the study area through the comprehensive application of laboratory testing, conventional logging data and special logging data. It is expected to establish a logging evaluation methodology system for shale reservoirs in this area, and have a clear understanding of the distribution of high-quality reservoirs, so as to provide a basis for the selection of shale gas target strata and the delineation of favorable areas in Yichang area.

1 GEOLOGICAL SETTINGS

The tectonic position of Yichang area is located in the southwestern margin of Huangling uplift of the Middle Yangtze Platform (Xu et al., 2019). The main strata range from the Nanhua System to Triassic and Cretaceous. Since the Indosinian Period, the Yichang area has been subjected to the superposition and composite of multi-phase and multi-direction structures, presenting a complex and orderly structure (Liu et al., 2010). On the plane, the tectonic patterns of hedging, superposition, interference are the typical characteristics (He et al., 2011). The study area is mainly located in Yichang slope belt, which is connected with Huangling uplift in the northwest, bounded by Tongchenghe fault in the northeast and Tianyangping fault in the southwest (Fig. 1). The surface of the slope belt is mainly covered by Cretaceous, and the strata are generally north to east trending. The seismic profile shows that the stratum in Yichang slope zone is very gentle, most of which are below 10°, and the faults are not developed. The study area mainly experienced the stable stages of Yangtze Craton deposition and sedimentation during the Caledonian and Hercynian periods (Zhang et al., 2019). Then, the development stages of tectonic deformation and displacement since the Indosinian Period. And the structural adjustment stages of compression and torsion since the Early Yanshanian Period, which established the basic tectonic pattern of Mesozoic and Paleozoic in this area (He et al., 2009). The thickness of the Lower Cambrian Shujingtuo Formation in the study area ranges from 24 to 104 m. It is mainly composed of lower carbonaceous shale with "pot bottom" limestone, limestone and upper marl with calcareous shale. During deposition period of the shale of Shuijingtuo Formation, the study area chiefly developed a deep-water shelf environment, primarily developed gray-black carbonaceous shale with siliceous rock and gray-green shale with marl rock, and generally with horizontal bedding (Chen et al., 2003). In addition to benthic Trilobites and self-swimming Trilobites, there were more Eodiscina living in floating (Jin et al., 2017). To the northeastern of the study area, the paleo-ocean gradually became shallow, and shallow-water shelf and shore facies were developed, and the thickness of black shale gradually decreased.

2 DATA AND METHODS

In the evaluating process of conventional reservoir, we can only obtain the general situation of reservoir parameters due to the limitation of the measured data. However, well logging data is with continuity and is closely related to rock physical parameters, so it is of high timeliness and accuracy to use well logging data for reservoir evaluation (Chen et al., 2009). During the evaluating process of the shale of Shuijingtuo Formation, this study is intended to seek the matching relationship between the geological parameters with logging data so as to establish the reservoir logging interpretation model of key parameters and form a set of evaluation logging interpretation evaluation methods of the shale in the region. Therefore, this study mainly includes three aspects, reservoir evaluation (mineral composition, porosity, gas bearing content), geochemical parameter evaluation (TOC), and mechanical property evaluation (Young modulus, Poisson ratio, brittleness index). The study mainly carried out systematic reservoir evaluation for Well EYY1. The Well EYY1 performed 84.71 m complete coring of the shale of Shuijingtuo Formation, and a large number of different type wire-line logs were implemented to evaluate the shale reservoir characteristics. The main wire-line logs include natural Gamma (GR), natural potential (SP), acoustic (AC), density (DEN), neutron (CNL), caliper (CAL), resistivity (RD), nuclear magnetic resonance (CMR), elemental capture spectroscopy (ECS), and sonic-scanner logging, etc. The conventional logging is carried out by Jianghan Oilfield of SINOPEC and the special logging is carried out by Schlumberger. At the same time, systematic reservoir and geochemical testing are carried out, mainly including mineral composition, porosity, gas bearing content, TOC and rock mechanics parameters, etc.

The tests were mainly completed by the Jianghan Oilfield of SINOPEC. Mineral components were identified using

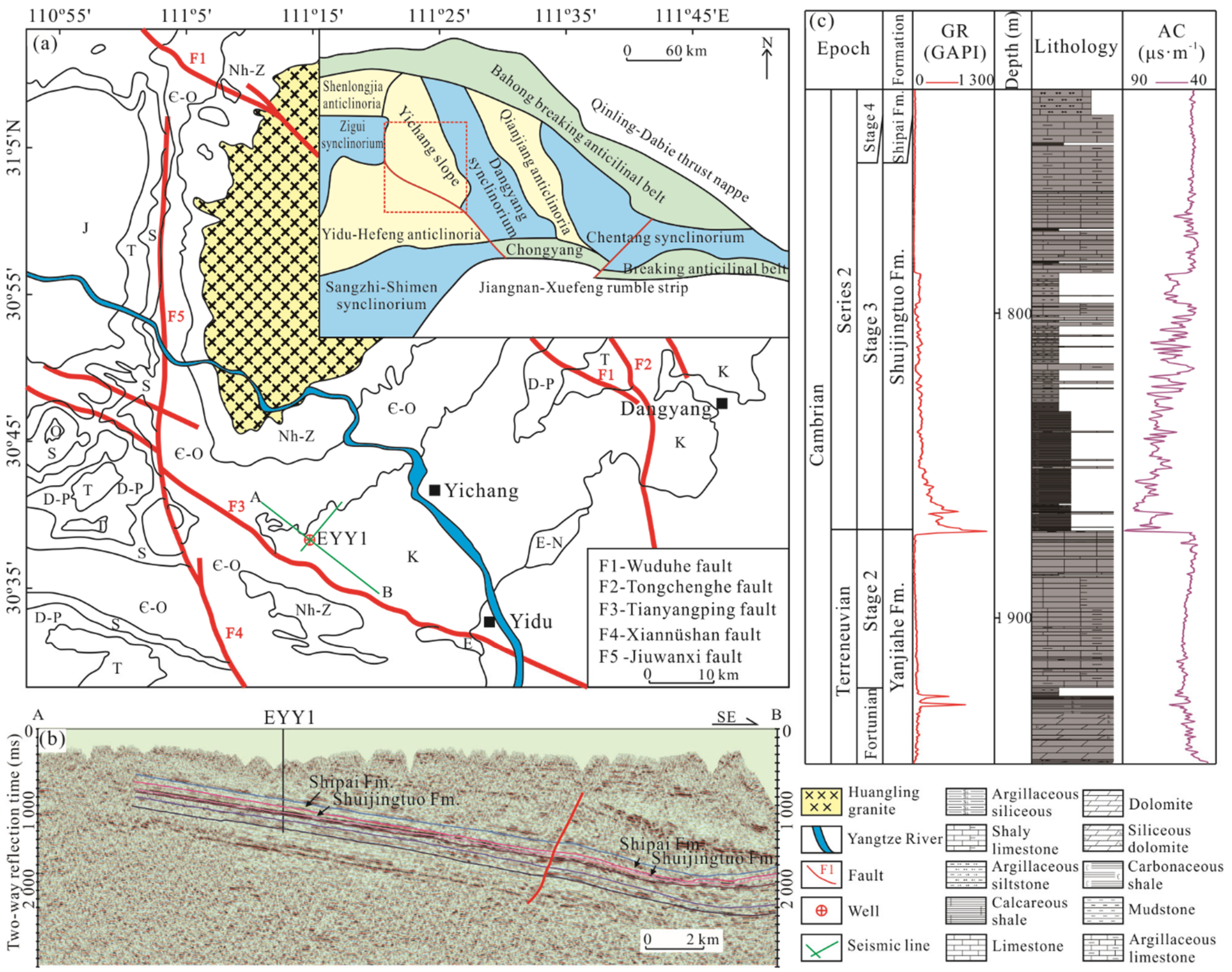

Figure 1. Location, geological map and Lower Cambrian in the Yichang area, Central Yangtze.

D8ADVANCE X-ray diffractometer made by Bruker of Germany. The shale powder sample, which had been ground to about 300 meshes, was placed in the center of the spectrometer for X-ray irradiation. X-ray intensity was detected and recorded to obtain the diffraction spectrum, and finally TOPAS software was used for quantitative analysis of shale mineral components. The PDP200 porosity and permeability analyzer was used for physical property test of shale with the method of gas expansion and pulse attenuation. The gas medium was helium and the test temperature was normal temperature. The working pressure and balance time were improved to select the optimal value to improve the testing accuracy. The gas bearing content was tested by the automatic instrument for field measurement of shale gas content based on drainage desorption gas collection method. The desorption adopted water bath heating and temperature control method. In the first stage, desorption lasted for 3 h with the method of mud circulation in the temperature of 38 ºC. Then, the temperature was 78–84 ºC for rapid desorption until the whole process was completed. The total organic carbon was tested by sulfur carbon analyzer of CS230 produced by LECO of the United States. Firstly, 50 mg of the grinding sample powder was added into a porcelain crucible which was soaked in hydrochloric acid with a mass fraction of 5%. It was heated at 80 ºC for 8 h. Then it was rinsed with pure water with 10 times so that the residual hydrochloric acid was removed. Finally, the sample was dried at 65 ºC and tested in the instrument. The total organic carbon content was calculated according to the CO^2 peak area generated at high temperature. Mechanical property was calculated from the logging data.

3 RESULTS AND DISCUSSION

3.1 Mineral Composition

Generally, the contents of brittle minerals and clay have a significant influence on the effect of reservoir fracturing (Wang et al., 2016). The reservoir with high brittle minerals content and low calcite content is with a relatively short drilling cycle and is easy to be fractured (Wang et al., 2013). Therefore, the evaluation of mineral content is particularly important for shale reservoir evaluation. At present, conventional logging combining with ECS logging is often used to evaluate the mineral composition of shale (MacDonald et al., 2012). The major elements measured by ECS logging include Si, Ca, Fe, S, Ti, Gd, etc. As the Si is closely related to quartz, Ca is closely related to calcite and dolomite, and Al is closely related to clay mineral content, the ECS logging data can be used to evaluate the mineral composition of shale by establishing the logging interpretation model.

The correlation analysis between core testing data and logging interpretation results proves the feasibility and effectiveness of the model. Figure 2 shows that the logging interpretation of quartz, carbonate and clay mineral content is in a moderate or good correlation with the core testing results. The correlation coefficients R^2 are 0.53, 0.61, and 0.42, respectively. The R^2 value between 0 and 0.2 is considered poor, 0.2–0.4 fair, 0.4–0.6 moderate, 0.6–0.8 good, and 0.8–1.0 almost perfect (McGinn et al., 2007). Therefore, ECS logging can be well used for mineral component evaluation. ECS interpretation data shows that the clay content at the lower part of the shale (1 850 to 1 872 m) decreases slightly, with an average of 25.3%, the calcite content decreases obviously, with an average of 17.3%, the quartz content is higher, with an average of 35.1%, the content of feldspar is low, while the pyrite increases to an average of 4.5% (Fig. 3). The calcite content at the upper part of the shale (1 786 to 1 850 m) is higher, with an average of 36.7%. The clay minerals are with an average of 27.5%. The quartz is with an average of 21.3%. The content of feldspar and pyrite is relatively low, less than 3% on average. It is showed that the content of brittle minerals (quartz and feldspar) at the lower part of the Shuijingtuo Formation is higher (Sondergeld et al., 2010). Previous studies have shown that the reservoir can have a good fracturing ability when the content of brittle minerals is more than 40% (Sondergeld et al., 2010). The logging interpretation results show that there is just the bottom 20 m segment of the Shuijingtuo Formation locally meeting the above conditions, which constitutes the most favorable reconstruction intervals.

3.2 Porosity

As the results of CMR measurement are not affected by the rock skeleton composition, and are sensitive to the flowing of pore fluid, which can accurately provide the porosity value in the stratigraphy, it is widely used in the shale porosity testing (Westphal et al., 2005). A method for calculating the true porosity of low porosity and low permeability reservoir is presented by combining acoustic and NMR (nuclear magnetic resonance) logging data (Mao et al., 2010). It can accurately provide the interval porosity relating to the pore throat radius and pore structure of the rock. The CMR porosity model is shown in Fig. 4. As can be seen from the figure, with the relaxation time increasing from left to right, it corresponds to muddy bound water, capillary bound water and movable water in turn. Movable water exists in relatively large pore space and generally has the longest relaxation time, corresponding to a relatively large T_2 spectral interval. Muddy bound water exists in very small micro-pores, and the echo signal is easily attenuated, which corresponds to the minimum relaxation time. The relaxation time of capillary bound water is between that of movable water and muddy bound water. The area enclosed by the CMR decay spectrum curve (T_2 spectrum) is proportional to the number of hydrogen nucleus in the pore fluid, so the T_2 spectrum of CMR log can be directly calibrated to the reservoir porosity (Li et al., 2016). The calculation formula of porosity is as follows

$$\Phi = \int_{T_{2i}}^{T_{2i+1}} S(T_2) dT_2$$

Φ is the porosity, %. T_2 is the relaxation time, ms. $S(T_2)$ is the distributed spectral function of T_2.

Based on the above principle of CMR test technology, this study proposes the CMR porosity to characterize the reservoir

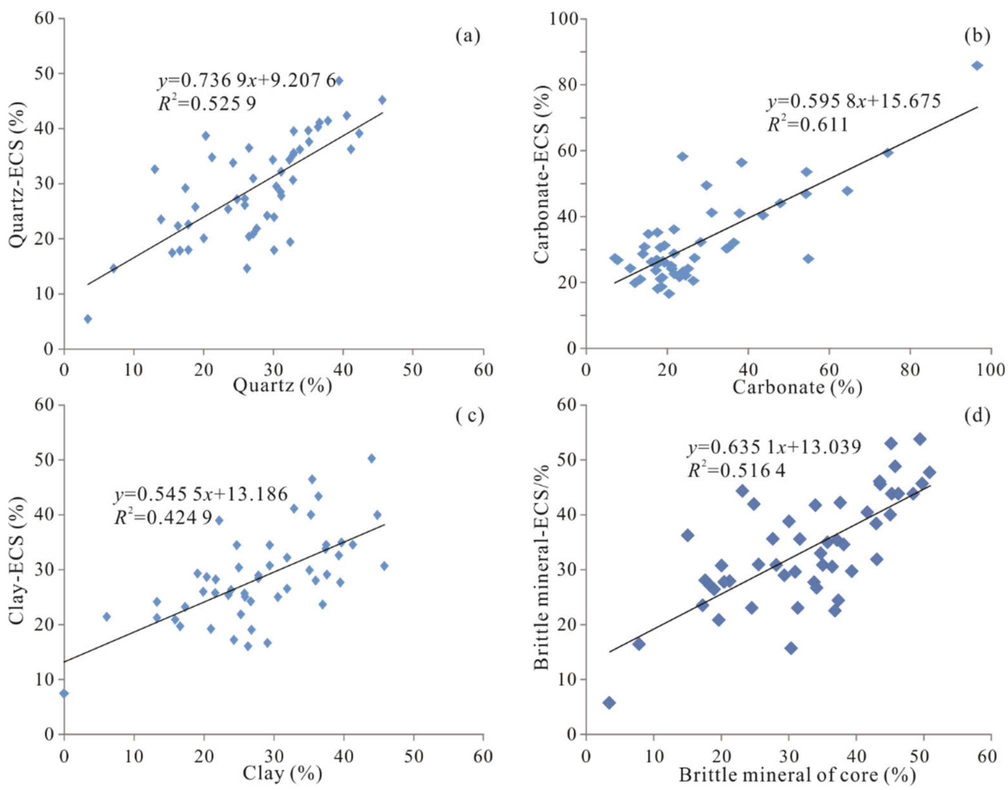

Figure 2. Cross-plot of mineral contents of core testing and elemental capture spectroscopy (ECS) logging interpretation from the shale of Shuijingtuo Formation in Well EYY1.

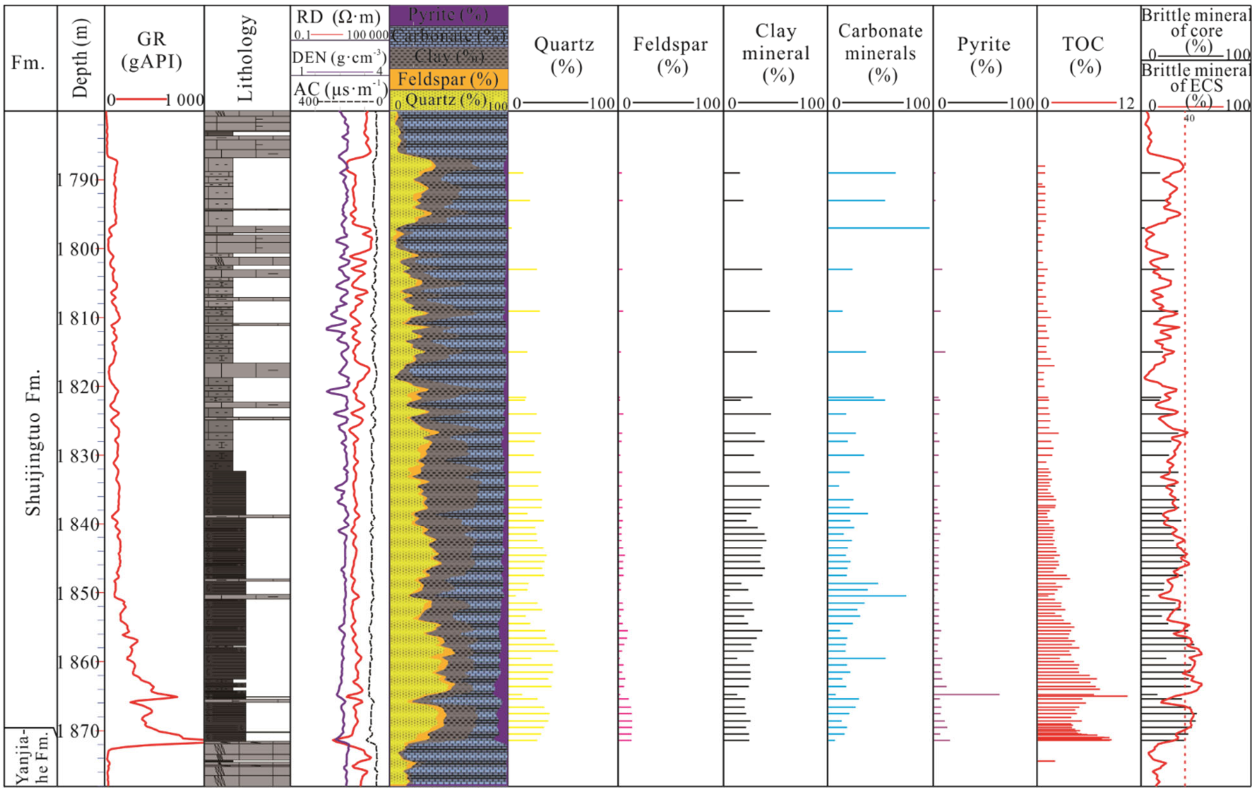

Figure 3. Mineral composition of the shale of Shuijingtuo Formation in Well EYY1. Fm. Formation.

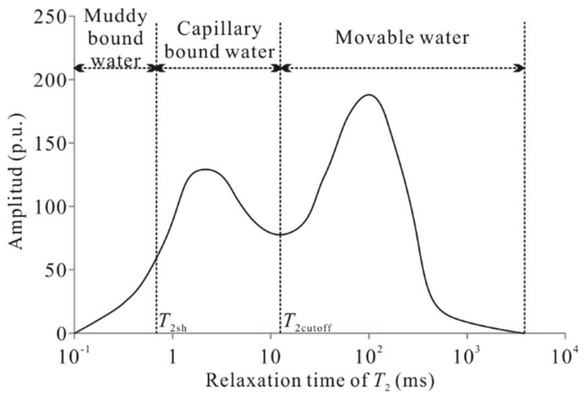

Figure 4. Porosity interpretation model of nuclear magnetic resonance (NMR).

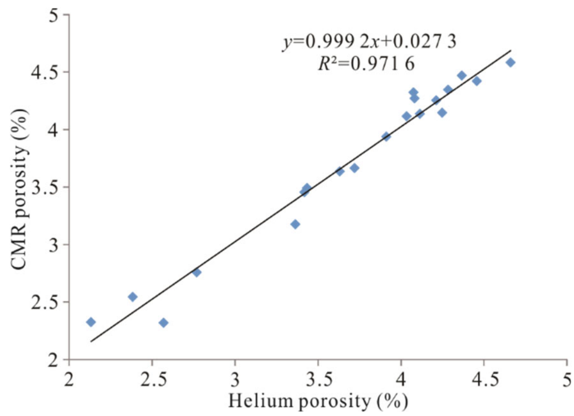

Figure 5. Cross-plot of helium porosity and combinable nuclear magnetic resonance (CMR) porosity of the shale of Shuijingtuo Formation in Well EYY1.

measurement technology and can obtain more accurate information of reservoir pore parameters. As can be seen from the correlation diagram of nuclear magnetic porosity and helium porosity tested in the laboratory, the correlation coefficient R^2 of the them is 0.97, indicating that nuclear magnetic porosity can well characterize the changes of shale porosity (Fig. 5). In addition, according to the distribution histogram of nuclear magnetic pores (Fig. 6), it can be seen that the ratio of medium to large pores of the lower section is higher than that in the middle section, showing that the ratio of medium to large pores gradually decreases from bottom to top. This indicates that the pore structure and effective porosity in the shale of Shuijingtuo Formation is gradually worse from the bottom to up, which is consistent with the results of core analysis. Previous studies have shown porosity characteristics. In Yichang area, the Schlumberger's CMR-plus is adopted. It adopts the modern pulse-echo that the pores of the shale in the study area are mainly composed of organic pores and inorganic pores, and the contribution of organic matter pores to porosity is relatively greater when the TOC is greater than 2%. Therefore, high abundance of TOC is conducive to the development of pore so that the high TOC shale shows high porosity (Li et al., 2019). According to the results of the nuclear magnetic porosity testing, the porosity of the shale of Shuijingtuo Formation decreases from bottom to top (Fig. 6). The porosity of the lower section is generally greater than 3%, while the porosity of the upper section is generally less than 3%, indicating that the lower section is a favorable shale gas storage segment.

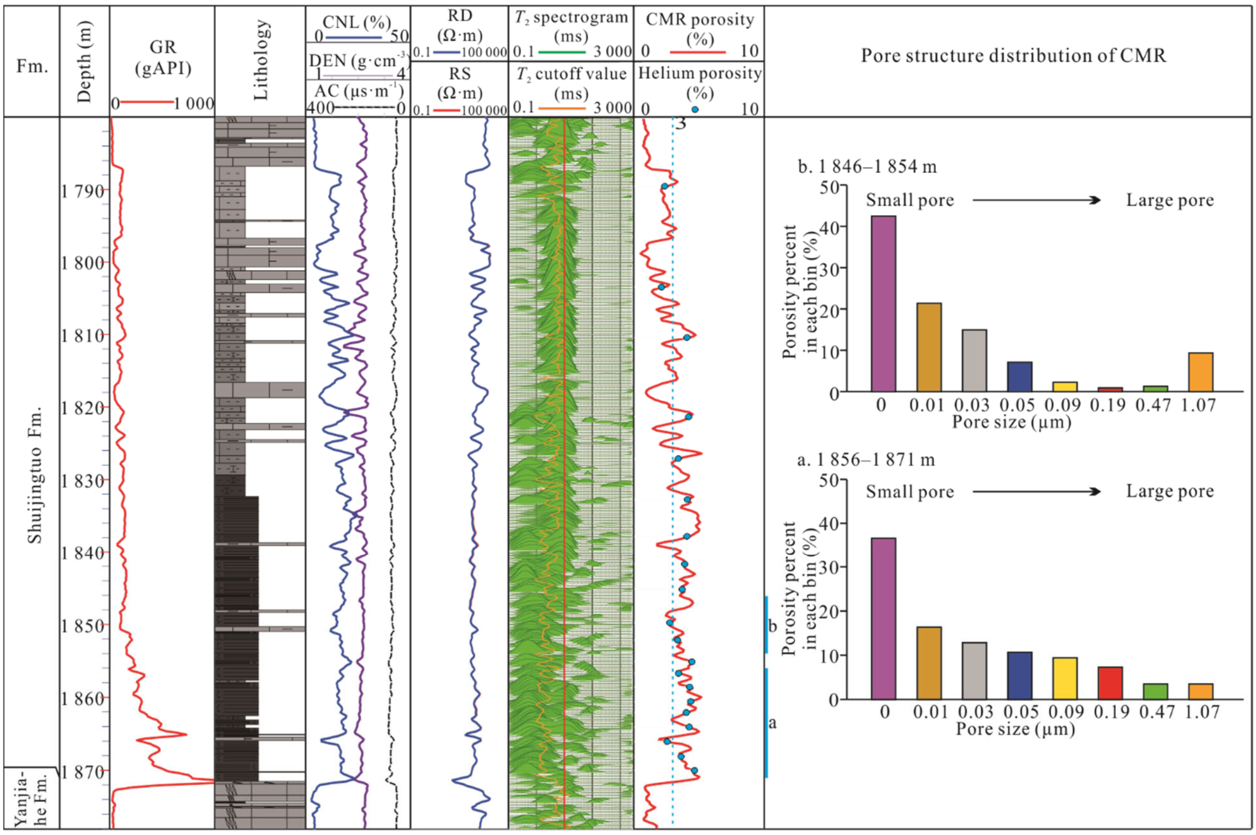

Figure 6. Combinable nuclear magnetic resonance (CMR) porosity and helium porosity of the shale of Shuijingtuo Formation in Well EYY1.

3.3 Gas Bearing Content

The gas bearing content refers to the volume of natural gas contained in each ton of shale under standard conditions. According to the occurrence state, the gas bearing content of shale is composed of adsorbed gas, free gas and dissolved gas (Pan and Connell, 2015). The gas bearing content testing is an important experiment to evaluate the quality of shale reservoir and optimize favorable zone. The testing methods include desorbed method, isothermal adsorption method, and the logging interpretation method (Diamond and Schatzel, 1998). The desorbed method is a direct method to test the gas bearing content, and also a most commonly used method. Isothermal adsorption and logging interpretation method are indirect methods for the gas bearing content. The accuracy of desorbed measurement of gas content mainly depends on two factors. One is try to reduce the loss of gas, and the other one is to simulate the stratigraphy conditions, especially the geothermal condition (Wei et al., 2007). As desorbed method is the most direct method to test shale gas content, the testing results are mainly used in this study.

In this study, the logging evaluation of gas bearing content is carried out by combining conventional logging data with desorbed method testing data. As it is shown on Fig. 7, the acoustic logging data is with a good linear correlation with the total gas volume and desorbed gas volume data. The correlation coefficients (R^2) are 0.607 3 and 0.611 9, respectively. Therefore, gas bearing content data can be fitted with acoustic logging data. The established logging interpretation model of gas bearing content is as follows.

$$TG = 0.158\ 1 \times AC - 9.026\ 2$$

$$DG = 0.071\ 6 \times AC - 3.832\ 9$$

TG is the total gas volume, $m^3 \cdot t^{-1}$. AC is the acoustic logging data, $\mu s \cdot m^{-1}$. DG is the desorbed gas volume, $m^3 \cdot t^{-1}$.

The gas bearing content of Shuijingtuo Formation is calculated by using the above logging interpretation models. The results show that the calculated gas bearing content of the model is in good agreement with the gas bearing content data, indicating the high accuracy of the model (Fig. 8). It shows that the total gas bearing content gradually decreases from the bottom to up, and the lower 20 m segment is generally greater than 2 $m^3 \cdot t^{-1}$, indicating that the lower segment is a shale gas enrichment layer.

3.4 Total Organic Carbon Content

Organic geochemical parameters are important parameters to evaluate the oil and gas abundance in shale (Lu et al., 2012). Organic matter has special physical properties, such as its poor conductivity, strong natural radioactivity, density closing to the density of water, belongs to the light component, acoustic closing to 550 $\mu s \cdot m^{-1}$, and hydrogen index closing to 67% (Murphy et al., 2008). The conventional logging cannot directly measure the TOC in shale reservoir, so it is necessary to establish the TOC logging calculation model of conventional logging data combining core testing data. Predecessors' research results show that the TOC can be evaluated by natural gamma ray, natural gamma ray spectrometry, resistivity, density and acoustic logging data according to the corresponding reflections on different well logging curves (Kamali and Mirshady, 2004). In this study, a TOC calculation model was established by combining well logging data with measured core TOC data, and the shale quality

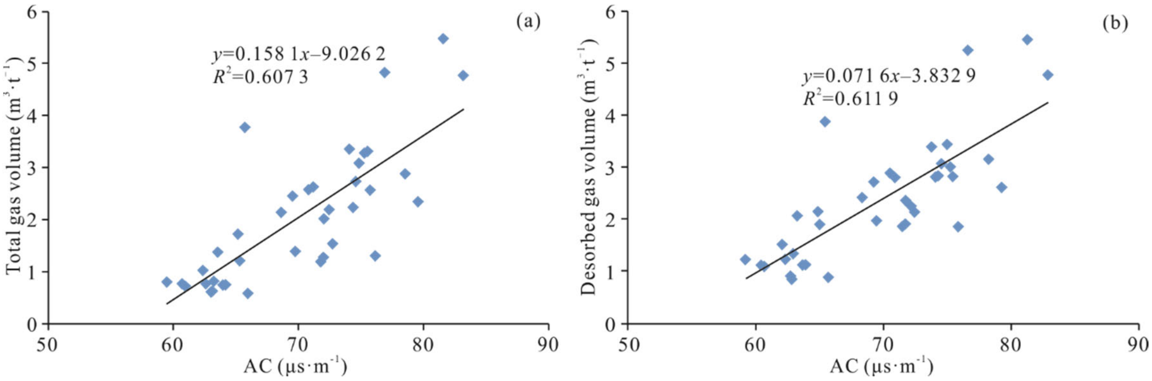

Figure 7. Cross-plot of AC (acoustic) log and gas bearing data of the shale of Shuijingtuo Formation in Well EYY1.

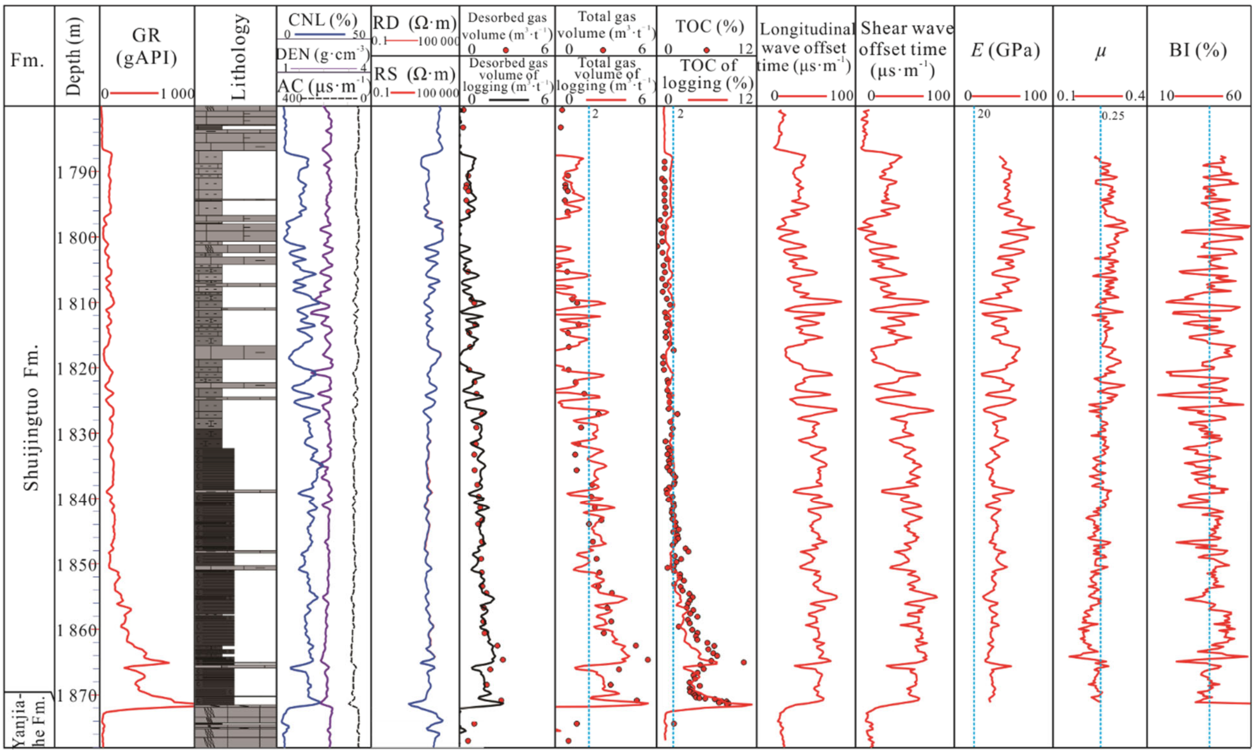

Figure 8. Logging interpretation of gas bearing content, total organic carbon content (TOC) and mechanical property of the shale of Shuijingtuo Formation in Well EYY1.

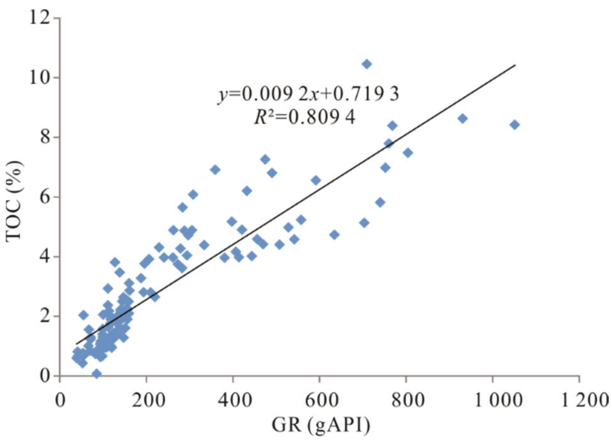

Figure 9. Cross-plot of GR (gamma ray) log and total organic carbon content (TOC) data of the shale of Shuijingtuo Formation in Well EYY1.

was evaluated. As it can be seen from Fig. 9, the correlation relationship between TOC and GR is excellent, and the correlation coefficient (R^2) is 0.81. Therefore, the relation of TOC logging interpretation model is established. The formula is as follows

$$\mathrm{TOC} = 0.009\ 2 \times \mathrm{GR} - 0.719\ 3$$

TOC is the total organic carboncontent, %. GR is the gamma ray logging data, gAPI.

The TOC of the shale of Shuijingtuo Formation is calculated by using the established logging interpretation model. The results show that the TOC gradually decreases from the bottom to the top, with a variation range of 0.86% to 11.83% (Fig. 8). The strata with TOC more than 2% are mainly located at the bottom of the Shuijingtuo Formation, which is the layer of organic matter enrichment.

3.5 Mechanical Property

Rock can be regarded as an elastic body under certain initial load, so its fracturing ability is mainly evaluated on the basis of brittle characteristics such as rock mechanical parameters (Maleki and Pouya, 2010). The mechanical parameters of rock mainly include Young modulus (E) and Poisson ratio (μ), while the deformation and stress of rock are usually linear, so the E and μ can be determined by the time difference between P-wave and S-wave (Saenger et al., 2011).

$$\mu = \frac{\Delta T_s^2 - 2\Delta T_p^2}{2\left(\Delta T_s^2 - \Delta T_p^2\right)}$$

$$E = \frac{\rho_b}{\Delta T_s^2}\left(\frac{3\Delta T_s^2 - 4\Delta T_p^2}{\Delta T_s^2 - \Delta T_p^2}\right)$$

ΔT_P is the offset time of P-wave, μs·m^{-1}. ΔT_S is the offset time of S-wave, μs·m^{-1}. E is the Young modulus, GPa. μ is Poisson ratio, dimensionless. ρ_b is rock density, g·cm^{-3}.

Based on the characterization of the above rock mechanical parameters, the rock brittleness was evaluated according to the relationship between the parameters and rock brittleness. Generally, the brittleness of rock includes two meanings, the difficulty of rock fracture under the action of external force and the difficulty of rock fracture remaining open after fracturing. They are evaluated by the index of Poisson ratio and Young modulus respectively. The smaller of the Poissonratio, the more likely the rock is to break under the action of external forces. The larger of the Young modulus, the more favorable it is for the rock to keep the fractures opening after producing cracks. The brittleness of rock is usually indicated by the brittleness index (Diao, 2013). The brittleness index of rock is calculated by Young modulus and Poisson ratio respectively, and the average value of them is taken as the comprehensive brittleness index of the rock (Yang et al., 2015). The maximum and minimum values of Poisson ratio and Young modulus are determined by actual data.

$$\mathrm{BI}_E = \frac{E - E_{\min}}{E_{\max} - E_{\min}} \times 100$$

$$\mathrm{BI}_\mu = \frac{\mu - \mu_{\max}}{\mu_{\min} - \mu_{\max}} \times 100$$

$$\mathrm{BI} = \frac{\mathrm{BI}_E + \mathrm{BI}_\mu}{2}$$

$E_{\min}$ is the minimum value of Young modulus, GPa. $E_{\max}$ is the maximum Young modulus, GPa. $\mu_{\min}$ is the minimum Poisson ratio. $\mu_{\max}$ is the maximum Poisson ratio. BI_E is the brittleness index of rock calculated by Young modulus, %. BI_μ is the brittleness index of the rock calculated by Poisson ratio, %. BI is brittleness index of rock, %.

Figure 8 is the evaluation result of the brittleness of the shale. The results show that the main Young modulus of the shale ranges from 26.11 to 81.07 GPa, with an average of 46.08 GPa, the Poisson ratio mainly ranges from 0.15 to 0.34, with an average of 0.26 and the brittleness index of shale mainly ranges from 15.18% to 66.74%, with an average of 40.73%. Previous studies have shown that the reservoir is relatively most conducive to fracturing when Young modulus is greater than 20 GPa, Poisson ratio is less than 0.25, and rock brittleness index is greater than 40% (Jiang et al., 2010). The continuous 15 m shale at the lower part of the Shuijingtuo Formation in the study area is with the above characteristics, and the maximum value of BI is in this section (Fig. 8; Fig. 10). Therefore, this section is with the optimal brittleness condition.

3.6 Comprehensive Reservoir Classification and Evaluation

Based on the analysis of above key parameters of shale reservoir, the comprehensive classification and evaluation of the shale of Shuijingtuo Formation were carried out by taking into account the mineral composition, porosity, gas bearing content, TOC and mechanical property. High shale gas production areas, especially in North America, often evaluated the reservoir quality by one or several reservoir parameters due to the complexity of geological conditions, and lack of a systematic classification standard of reservoir evaluation parameters. It is showed that the basic criteria for high-quality shale reservoirs include high brittle mineral content (more than 40%), high organic matter abundance (TOC>2%), porosity more than 3%, gas bearing content more than 2 m^3·t^{-1}, Poisson ratio less than 0.25, and rock brittleness index more than 40% (He et al., 2015; Xiao et al., 2013). Among them, the gas bearing property of the reservoir is the most important reference factor. When the gas bearing property of the reservoir is less than 1 m^3·t^{-1}, the quality of reservoir is relatively poor (Bi et al., 2014). Therefore, combining with the basis of reservoir classification and evaluation standards from the domestic and overseas, the shale of Shuijingtuo Formation is mainly classified into three types of reservoirs in this study, and the classification criteria are shown in Table 1.

Based on the above criteria and the evaluation results of reservoir parameter, the reservoir parameters are comprehensively characterized (Fig. 11). The Type I reservoir is mainly located at the bottom, with a total thickness of 8.5 m. Type II is mainly located at the middle section, with a total thickness of 44.38 m. The other reservoirs are classified as Type Ⅲ, mostly located at the upper section, with a total thickness of 31.83 m. Among them, the Type I reservoir is optimal, the Type II is general, and the Type III is the worst.

The Type I is chiefly made of carbonaceous shale and the gas bearing content is about 2 to 4.37 m^3·t^{-1}, with an average of 3.16 m^3·t^{-1}. The content of brittle minerals is about 40% to 60%, 49.9% in average. TOC ranges from 2% to 5.3%, 3.6% in average. The porosity ranges from 3% to 5.24%, 4.08% in average. μ is about 0.19 to 0.25, 0.21 in average. The BI is about 40% to 60.9%, with an average of 47%. On the whole, this type reservoir is with the best quality and meets all the criteria of high quality reservoir.

The lithology of Type II reservoir is mainly carbonaceous shale and grey shale. The gas bearing content is about 1 to 4.46 m^3·t^{-1}, with an average of 2.28 m^3·t^{-1}. The content of brittle minerals is about 11% to 56.78%, 30.9% in average. TOC ranges from 1.43% to 7.88%, 2.39% in average. The porosity is about 1.7% to 5.13%, 3.67% in average. μ is about 0.19 to 0.33, 0.25 in average. The BI is about 16.12% to 53.78%, 38.71% in average. Generally speaking, this type reservoir is next to Type I, with the gas bearing content more than 1 m^3·t^{-1} and at least one of the other reservoir parameters meets the above criteria.

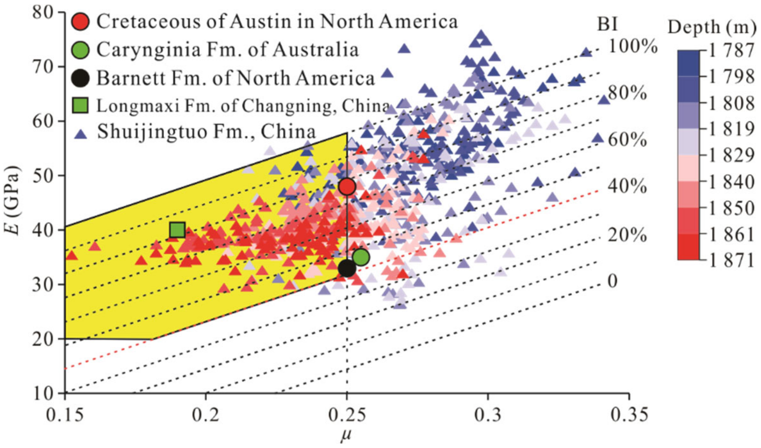

Figure 10. Distribution diagram of rock mechanics parameters and brittleness index for the shale of Shuijingtuo Formation in Well EYY1.

Table 1 Criteria for the reservoirs classification of the shale of Shuijingtuo Formation

Reservoir type	Criteria for the classification
Type I	Gas bearing content more than 2 $m^3 \cdot t^{-1}$, the content of brittle minerals more than 40%, TOC more than 2%, porosity more than 3%, Poisson ratio lower than 0.25, and brittleness index more than 40%
Type II	Gas bearing content more than 1 $m^3 \cdot t^{-1}$, the content of brittle minerals more than 40%, TOC more than 2% or porosity more than 3% or Poisson ratio lower than 0.25 or brittleness index more than 40%
Type III	Gas bearing content lower than 1 $m^3 \cdot t^{-1}$, the content of brittle minerals lower than 40%, TOC lower than 2% or porosity lower than 3% or Poisson ratio more than 0.25 or brittleness index lower than 40%

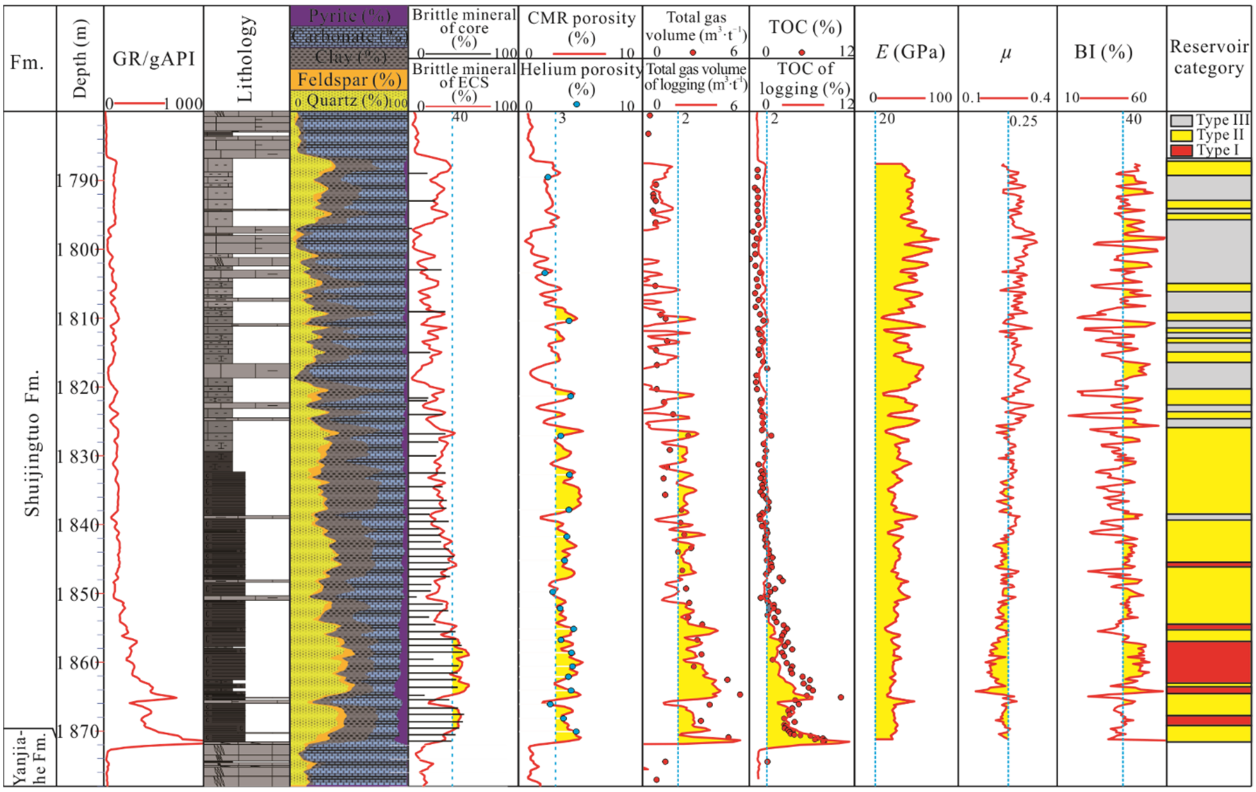

Figure 11. Comprehensive reservoir classification and evaluation of the shale of Shuijingtuo Formation in Well EYY1.

The lithology of Type III is primary ash shale and calcareous shale. The gas bearing content is about 0 to 1 $m^3 \cdot t^{-1}$, with an average of 0.55 $m^3 \cdot t^{-1}$. The content of brittle minerals is about 3.35% to 36.44%, 17.73% in average. TOC is about 1% to 1.98%, 1.47% in average. The porosity ranges from 0.49% to 4.22%, 2.19% in average. μ is about 0.21 to 0.34, 0.28 in average. The BI ranges from 19% to 58.63%, 42.88% in average. In general, the quality of this type reservoir is the worst. The gas bearing content is less than 1 $m^3 \cdot t^{-1}$, and at least one of the other reservoir parameters does not meet the above standard of high quality reservoir.

4 CONCLUSIONS

(1) Based on the results of conventional logging data, special logging data and core testing data, the characterization method and model of shale reservoir were established by geophysical logging, including mineral composition, porosity, gas bearing content. The results show that the shale at the lower section of the Shuijingtuo Formation is with the maximum brittle mineral content, the highest porosity and the best gas content, which is the shale gas enrichment section.

(2) The TOC logging interpretation model of the shale is established by combining the conventional logging data with the measured core TOC data, which can better reveal the development characteristics of the TOC. The strata with TOC more than 1% are mainly located at the bottom of the Shuijingtuo Formation, and is the organic matter enrichment segment.

(3) Based on sonic-scanner logging data, the geophysical logging interpretation model of mechanical properties was established and the characteristics of reservoir mechanical parameters were analyzed. The continuous 15 m shale at the lower part of the Shuijingtuo Formation is with the characteristics of relatively optimal low Poisson ratio, high Young modulus and high brittleness index, which is with the optimal brittleness condition.

(4) According to the standard of high quality reservoir, the shale of Shuijingtuo Formation in the study area is divided into three types, including the optimal reservoir Type I, mainly located at the bottom, with a total thickness of 8.5 m, the Type II next to Type I, mainly located at the middle, with a total thickness of 44.38 m, the worst Type III, mainly located at the upper, with a total thickness of 31.83 m.

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