Comprehensive evaluation of coal-bearing tight sandstone reservoir logging in the Benxi Formation, east-central Ordos Basin

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Abstract: The tight sandstone reservoirs of the Benxi Formation are characterized by low pore and low permeability inhomogeneity, etc. It is important to conduct a comprehensive evaluation study on the characteristics and logging of the tight sandstone reservoirs of the Benxi Formation for exploration and development. The study focuses on the application of imaging logging data such as nuclear magnetic resonance (NMR) and array acoustic wave, combined with conventional logging, to carry out the characterization and comprehensive logging evaluation of coal-bearing tight sandstone reservoirs. The study shows that the rock types of tight sandstone of Benxi Formation include quartz sandstone and rock chip quartz sandstone; the porosity is mainly distributed in (1.5%~4.5%) and the permeability is mainly distributed in (0.01mD~0.3mD). The porosity was solved by NMR logging; the permeability was solved by SDR calculation model; the water content saturation was solved by Indonesian equation considering the influence of mud; and the mud content of logging curve was solved by CGR, all of which achieved good agreement with the results of assay analysis. Various methods were used to discriminate the gas content of the reservoir. The rock brittleness indices calculated using sonic imaging and lithology scanning logs are consistent with each other.

1 Introduction

Tight sandstone gas is a typical unconventional gas with low porosity and low permeability, and has become the most realistic unconventional gas resource in China with the advancement of exploration and development technology . In the east-central part of the Ordos Basin, coal-bearing dense sandstone reservoirs are mainly developed in the Carboniferous Benxi Formation, Taiyuan Formation and Permian Shanxi Formation, with coal seams and mudstones as the main hydrocarbon source rocks . The exploration and development of dense sandstone gas in the Shanxi Formation in the central-eastern part of the Ordos Basin has reached a certain scale [7-8], while the research on the characteristics and logging evaluation of dense sandstone reservoirs in the Carboniferous Benxi Formation is still in its initial stage. A comprehensive evaluation of the reservoir characteristics and logging of the dense sandstone of the Carboniferous Benxi Formation will not only provide an effective evaluation tool for further exploration and development of coal-derived dense sandstone gas, but also provide an effective guarantee for increasing the storage and production of coal-derived unconventional energy.

As one of the important tools for reservoir evaluation, geophysical logging has been developed in recent years, such as lithology scanning logging, array induction logging, micro-resistivity scanning imaging logging, nuclear magnetic resonance logging and other new technologies, which have a broader prospect in the interpretation and evaluation of tight sandstone reservoirs [9-12]. For dense sandstone reservoirs, logging evaluation of the reservoirs has been carried out individually or partially integrated using conventional logging and imaging logging, and certain research results have been achieved, but further research is needed for the geological characteristics of the reservoirs and comprehensive evaluation of logging for the coal-bearing dense sandstone reservoirs of the Carboniferous Benxi Formation.

2 Geological characteristics of the reservoir

In the study area, 51.39% of the Benxi Formation rock chip quartz sandstone, 30.56% of the quartz sandstone and 18.06% of the rock chip sandstone; the sandstone chip composition is dominated by quartz and rock chip, with a higher average content than that of the Shanxi Formation. The average content of cement is low, mainly kaolinite, illite, siliceous, iron calcite, iron dolomite and chlorite. In terms of particle size, the reservoir mineral grains are relatively concentrated in size distribution, with rolling and suspension rolling (N-O-P) and suspension and rolling (P-Q) dominating; medium-grained quartz sandstone dominates, with some distribution of fine sand and less siltstone content.

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According to the analysis of the thin section identification results, the sandstone reservoir of the Benxi Formation in the study area has a medium-good sorting grade, a sub-rounded-sub-ribbed grinding degree, and a pore type of cementation. The physical properties of the reservoir are poor, with a maximum porosity of 12.49%, a minimum value of 0.22% and an average of 5.9%. Among them, the coarse sandstone porosity is mainly distributed between 4.5% and 9%, and the porosity in this interval accounts for 78.9% of all samples. The maximum value of reservoir permeability is $9.21\times10^{-3}\mu m^2$, the minimum value is $0.004\times10^{-3}\mu m^2$ and the average value is $0.7\times10^{-3}\mu m^2$.

3 Reservoir lithology evaluation

For the simpler formations in the study area, a qualitative discrimination of lithology can be made on the basis of differences in the response characteristics (Table 1) of the different lithologies on the various types of logging curves.

Table 1 Logging response characteristics of lithology

Logging curve	Mudstone	sandstone	Conglomerate sandstone	Conglomerate
GR(API)	104-176	100-140	102-165	70-25
AC(μS/ft）	62-90	60-86	58-84	54-72
DEN(g/cm³)	2.3-2.64	2.48-2.66	2.48-2.66	2.48-2.66
CNL(%)	6.0-26.0	5.0-22.0	5.0-14.0	2.0-10.0
RD.RS(Ω.m)	5-45	10-50	10-65	10-75

3.1 Lithology identification for GR and PE logging

Using PE logging alone, an adjunct to lithology can be carried out: with a low GR curve and a natural gamma energy spectrum showing low K, when the Pe value is close to 2, the lithology is sandstone; when the Pe value is around 3.14, the lithology is dolomite; and when it is close to 5, the lithology is calcite. Using GR and PE rendezvous, rock types can be classified (Figure 1). In general, quartz sandstone Pe<2.2, rock chip sandstone Pe>2.2, rock chip quartz sandstone Pe=1.8-2.8; coarse sandstone GR=25-55 API, medium sandstone GR=55-85 API and fine sandstone GR=85-120 API.

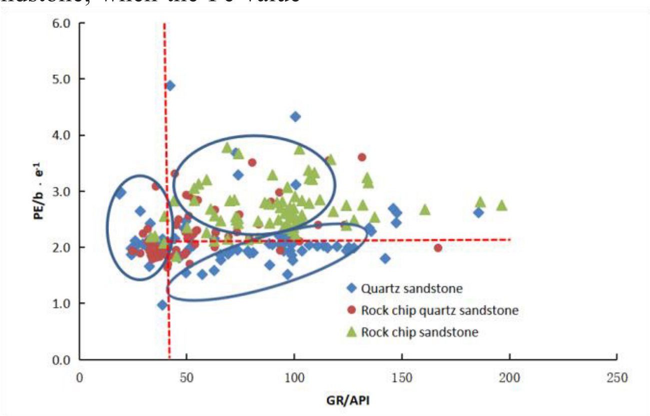

Figure 1 GR and PE lithology identification rendezvous

3.2 Lithological identification of neutron and density limestone porosity

The density logging curve is used to solve for density limestone porosity and is overlaid with neutron logging, using the difference between the two to make a qualitative visual determination of lithology (Table 2).

Table 2 Correspondence of skeletal minerals with different differences in neutron density

Curvilinear relationships	Approximate difference (%)	Possible skeletal minerals
$\Phi_D >> \Phi_N$	40	Rock salt
$\Phi_D = \Phi_N$	0	Limestone
$\Phi_D \ll \Phi_N$	>30	Coal seams
$\Phi_D < \Phi_N$	16	Hard gypsum
$\Phi_D > \Phi_N$	5-6	Sandstone
$\Phi_D < \Phi_N$	8-13	Dolomite
$\Phi_D << \Phi_N$	10-30	Mudstone

4 Reservoir parameter logging interpretation and evaluation

1. Porosity

By comparing the NMR logging data with the core analysis data, a capillary bound water cut-off value T_{2c} can be determined on the T_2 curve to distinguish free fluid porosity from capillary bound water porosity. The area enclosed by a portion of the T_2 curve greater than

T_{2c} represents the free fluid porosity, while the area enclosed by a portion less than T_{2c} represents the capillary bound water porosity. Thus, the total porosity, free fluid porosity and bound water porosity can be derived from the following integrals respectively. The NMR log curves were solved for porosity and compared with the assayed porosity and the agreement between the two was high (Figure 2).

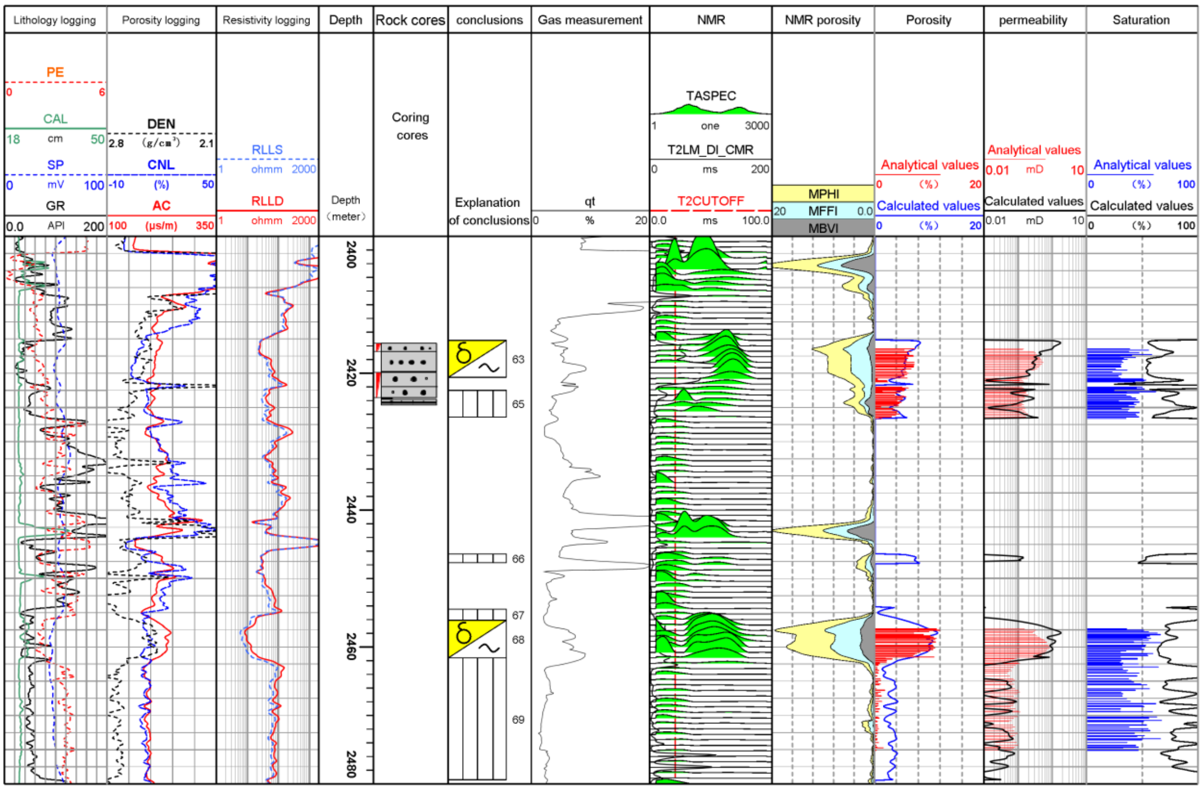

Figure 2 Results of reservoir parameter calculations

2. Permeability

Due to the complexity of the pore structure of the low porosity and low permeability reservoir rocks, the SDR permeability model was used to solve the NMR log curves for permeability (Eq. 1) when building the permeability interpretation model, which is in good agreement against the assay analysis results (Fig. 2).

$$K = C_{S1}(\phi_{NMR}/100)^4 \times T_{2g}^2 \quad (1)$$

where:C is a constant, C=1; φ_{NMR} is the nuclear magnetic porosity; T_{2g} is the T_2 geometric mean.

3. Gas content saturation

The calculation of gas saturation must take into account the influence of mud, so the Indonesian formula for gas saturation (Eq. 2-3) is chosen to take into account the influence of mud.

$$S_W = \sqrt[n]{\frac{a \times R_W \times R_{sh}}{R_t\left[V_{sh}^{\left(1-\frac{V_{sh}}{2}\right)}(aR_W)^{0.5} + \emptyset^{m/2} \times R_{sh}^{0.5}\right]^2}} \quad (2)$$

$$S_g = 1 - S_w \quad (3)$$

Where: S_w is the formation water saturation, %; S_g is the formation gas saturation, %; *Rt* is the formation resistivity, using deep lateral (RLLD), Ω·m, or other deep resistivity measurements if RLLD is not available; R_w formation water resistivity, Ω·m; *m,n* are rock and electricity experimental parameters.

This formula is an empirical formula. Through the statistics of mudstone resistivity of several wells in the study area, the average value of mudstone resistivity in the study area is 25 Ω·m, and the distribution range of formation water resistivity is 0.04-0.06. Based on the results of rock and electricity experiments in this area, the values of *m* and *n* in the Indonesian formula are determined to be 1.6 and 4.4 respectively.

Using the Indonesian formula to solve the gas-bearing saturation calculation results, Figure 2 shows the comparison between the analysis of the gas-bearing saturation content and the calculation results, which can be seen that the calculation results are basically consistent with the analysis results.

5 Gas content evaluation

5.1 Triple porosity logging overlay method

Triple porosity logging, which includes compensated density logging (DEN), acoustic logging (AC) and compensated neutron logging (CNL), is an important logging profile used to calculate reservoir porosity. Neutron logging mainly reflects the hydrogen index of the rock. If the pore space contains natural gas, the neutron porosity is low compared to water and oil formations with the same porosity, while natural gas increases the sonic porosity and density limestone porosity. The neutron porosity calculation is significantly lower than the acoustic porosity and density limestone porosity calculation due to the "mining effect" of neutron logging in gas-bearing formations, and based on this feature, the difference between the three porosities can be used to indicate the gas formation and evaluate the gas content of the reservoir. The triple porosity logging overlap method consists of two methods, namely the neutron and density limestone porosity overlap method and the neutron and acoustic porosity overlap method.

5.2 Array acoustic logging rendezvous method

The pore structure of the reservoir in the study area is complex, and the reservoir is characterised by low porosity, low permeability and non-homogeneity, making the identification of reservoir fluids difficult. This paper uses dipole sonic logging data to establish the longitudinal and transverse wave velocity ratio difference as a gas identification index for fluid identification, and uses the rendezvous analysis method to study the interrelationship between various elastic properties of rocks and determine the elastic parameters that can distinguish the lithology and gas content of the reservoir, improving the accuracy of fluid identification.

When the rock is saturated with natural gas, it increases the longitudinal wave time difference, leaving the transverse wave time difference essentially unchanged, resulting in an increase in the longitudinal to transverse wave ratio. Therefore, the gas reservoir can be indicated by the difference between the longitudinal and transverse wave time difference ratio when fully saturated with water and the measured longitudinal and transverse wave time difference ratio. When the reservoir contains gas, the longitudinal and transverse wave time difference ratio of the rock is calculated using equation (4).

$$DTR = \sqrt{\left[K_d + \frac{4}{3\mu_d} + \frac{(1-\beta)^2}{1-\emptyset-\frac{\beta}{K_{ma}+\frac{\varphi}{K_f}}}\right]\frac{1}{\mu_d}} \qquad (4)$$

When the reservoir is fully water-bearing, the longitudinal and transverse wave time difference ratio of the rock is calculated using equation (5).

$$DTRW = \sqrt{\left[K_d + \frac{4}{3\mu_d} + \frac{(1-\beta)^2}{1-\emptyset-\frac{\beta}{K_{ma}+\frac{\varphi}{K_w}}}\right]\frac{1}{\mu_d}} \qquad (5)$$

where: *DTR* is the longitudinal and transverse wave time difference ratio of rock when the reservoir contains gas, dimensionless; *DTRW* is the longitudinal and transverse wave time difference ratio of rock in a pure water layer, dimensionless; μ_d is the dry rock shear modulus, GPa; K_w is the formation water bulk modulus, GPa; K_d is the dry rock bulk modulus, GPa, and K_{ma} is the rock matrix bulk modulus, GPa; φ is the porosity, dimensionless; β is the Biot coefficient, dimensionless dimension.

Fluid identification criteria: the actual aspect ratio DTR obtained from acoustic full-wave data is compared with the actual aspect ratio DTR. When the aspect ratio measurement is greater than the pelagic background value, i.e. when the aspect ratio velocity ratio is less than the pelagic background value, it is considered to be a gas layer.

5.3 Nuclear magnetic resonance logging (NMR) identification method

One of the advantages of NMR logging is that it can identify pore fluids without regard to the rock skeleton. The difference in longitudinal relaxation time T_1 between water and light hydrocarbons is significant, with water being fully magnetised in a relatively short polarisation time, while light oil and gas require a longer polarisation time to be fully magnetised. In the differential and shift spectrum processing, the gas formation can be identified more accurately by using the natural gas relaxation time of the formation after core scaling and the cut-off value of the bound fluid. The method of gas formation identification using the gas spectrogram after NMR differential and shift spectrum processing is called the NMR T_{2Gas} gas spectrogram method.

5.5 Comparison of the effects of gas-bearing evaluation methods

The above methods were combined to evaluate the gas content of a well (Figure 3), and the results of the methods were compared (the ninth channel is the longitudinal and transverse wave time difference method, the tenth, eleventh and twelfth channels are the compression coefficient method, the thirteenth and fourteenth channels are the triple porosity logging, and the fifteenth channel is the nuclear magnetic method): the nuclear magnetic resonance logging indicates the gas content of dense sandstone significantly, especially in the microporosity. Regardless of the coarseness of the reservoir rock, the array sonic logging gives a clear indication of gas content, but the triple porosity logging overlap method only gives a clear indication when the sandstone is coarse grained, and when the sandstone is fine grained, the triple porosity logging overlap method may show weak gas content even if the reservoir is well grained, which may lead to misjudgement. The higher the difference between the array sonic logging rendezvous and the triple porosity logging overlay, the better the gas content.

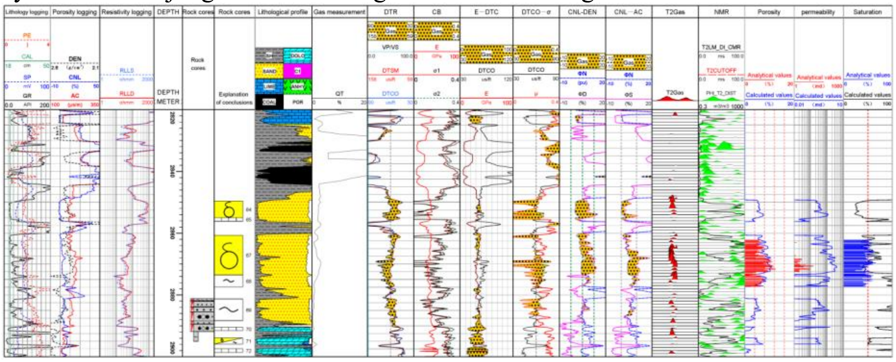

Figure 3 Gas content evaluation

6 Reservoir compressibility evaluation

The low porosity and low permeability of tight sandstone gas necessitates large scale fracturing to obtain industrial production, making compressibility evaluation essential. In this paper, work is carried out on the calculation of the brittleness index.

6.1 Calculation of brittleness index using rock elastic parameters

In this study, the longitudinal and transverse wave velocities of the formation can be obtained using array acoustic logging, and the Young's modulus and Poisson's ratio of the formation can be calculated by combining with the formation density, based on which the brittleness index of the formation can be calculated using the following empirical equations (Eqs. 6-8).

Young's modulus:

$$BI_{YM} = 100 \times \frac{YM - YM_{min}}{YM_{max} - YM_{min}} \tag{6}$$

Poisson's ratio:

$$BI_{PR} = 100 \times \frac{PR - PR_{min}}{PR_{max} - PR_{min}} \tag{7}$$

Brittleness Index:

$$BI = \frac{BI_{YM} + BI_{PR}}{2} \tag{8}$$

The Poisson's ratio reflects the ability of the rock to fracture under external forces, while Young's modulus (E) reflects the ability of the rock to support itself after fracturing. The higher the Young's modulus and the lower the Poisson's ratio, the more brittle the rock and the more likely it is to form a complex network of seams during fracturing.

6.2 Calculating the brittleness index using mineral content

It has been found that the content of brittle minerals such as quartz and calcite in rocks has an important influence on the brittleness index of rocks. In general, apart from calculating the brittleness index of a formation using elastic parameters, the brittleness index of rocks can also be evaluated by using the proportion of brittle mineral content to the total mineral content. In this study the degree of brittleness can be characterised by the percentage of quartz group (including quartz, feldspar and pyrite) (equation 9).

The brittleness index is calculated by:

$$B_{rit} = \frac{W_{QFR} + W_{Carb}}{W_{tot}} \tag{9}$$

Where: B_{rit} is the brittleness index, 0~1; W_{QFR} is the total content of quartz, feldspar and mica; *WCARb* is the carbonate rock mineral content (mainly including dolomite, calcite and other carbonate components); and *Wtot* is the total mineral quantity.

Figure 4(Last course) shows a comprehensive graph of rock brittleness evaluation using a combination of elastic modulus and mineral fraction analysis for the Benxi Formation in a well in the study area. From the figure, it can be seen that the brittleness index (BI_LS) calculated by lithological scanning logging is consistent with that calculated by acoustic scanning logging (BI), with smaller differences in mudstone and slightly larger differences in sandstone.

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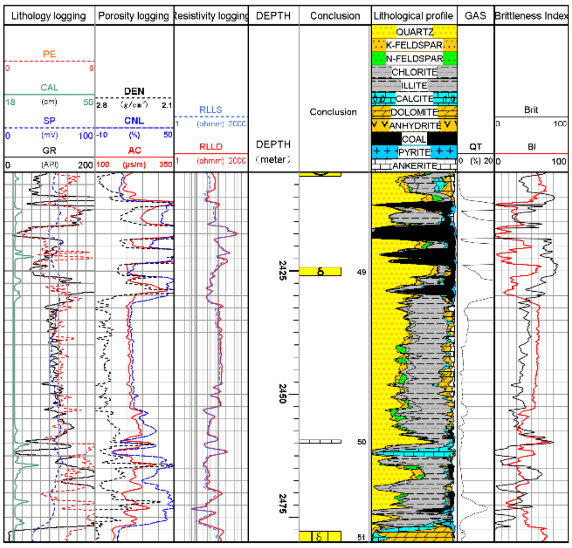

Figure 4 Calculation of the brittleness index

7 Conclusions

(1) By combining conventional logging with imaging logging (lithology scanning, electrical imaging, NMR, acoustic imaging), multiple methods are used to solve for reservoir physical parameters: NMR logging for porosity and permeability; Indonesia formula for permeability; and CGR for mud content.

(2) By conventional logging, combined with imaging logging (lithology scanning, electrical imaging, NMR and acoustic imaging), a total of four types of methods, namely triple porosity logging overlap method, array acoustic logging rendezvous method, NMR logging identification method and array induction logging identification method, are combined to make gas-bearing judgments and their effectiveness is compared.

(3) The brittleness index is solved using two methods: modulus of elasticity and mineral fraction.

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