Introduction

Carbonate reservoirs are important unconventional oil and gas reservoirs, and cracks and pores occur widely in these reservoirs. Such reservoirs have good reservoir and permeability properties and have recently become an important research direction for energy exploration (Nazemi et al., 2018). However, due to the existence of cracks and pores, reservoir heterogeneity is enhanced, and their geophysical characteristics are very complicated, which results in reservoir fluid identification difficulties (Yue et al., 2018). In recent years, many scholars have studied fluid identification in such reservoirs from the perspectives of geology, geophysics and geochemistry.

Geophysical logging has a unique advantage in reservoir fluid identification due to its high resolution. In recent years, geophysical logging has spawned new technologies, such as resistivity imaging and nuclear magnetic resonance logging. Traditional logging methods combined with new technologies have further improved the accuracy of fluid identification based on logging methods. Yi Han et al. (2019) combined mercury intrusion and thin section experiments and nuclear magnetic resonance logging, and a pore structure classification standard of carbonate reservoirs was founded, while the actual data were processed with the rotating forest algorithm. The accuracy of the classification results reached 98.56%. Ali Rajabi et al. (2015) utilized conventional logging such as gamma and density logging combined with dipole acoustic and nuclear magnetic resonance logging to establish a reservoir porosity calculation model by using the least squares method, and they used the model to calculate reservoir fluid reserves.

The above methods for identifying reservoir fluids based on geophysical logging methods have greatly improved the accuracy of fluid identification in carbonate reservoirs. However, new techniques are very expensive, although microresistivity scanning imaging and nuclear magnetic resonance logging techniques currently have a high resolution, but the detection depth is relatively shallow. In this paper, the elastic theory of porous and fractured media is improved. A petrophysical template suitable for qualitative carbonate reservoir identification is proposed. The actual logging data were processed by using the gas-bearing identification template founded on the above research conclusions. The identification results were essentially consistent with the production result.

Method

Twenty typical rock samples from the X1 well in the Sichuan Basin were selected, with a porosity ranging from 0.5% to 4.5%, with an average of 2.35%, and a permeability ranging from 0.05 to 5 mD. Thirty-five typical rock samples were selected from the X2 well, with a porosity ranging from 1% to 10%. The average porosity is 4.73%, and the permeability ranges from 0~0.4 mD. Experimental analysis of thin sections shows that the reservoir clay content of the two wells is low, mainly from 2~5%. All samples are fully saturated with a 47622 ppm NaCl solution, and an HSN-B intelligent acoustic velocity measuring device is used to measure the P- and S-wave velocities of the saturated samples. Then, a high-speed refrigerated centrifuge is used, and during centrifugation, the acoustic velocity of the samples under different saturation conditions are measured with the device until the water saturation of the sample does not change, indicating that the bound water state is reached, after which the experiment is stopped.

Porous and fractured media are the focus of petroleum exploration. Biot (1956) proposed the elastic wave theory of porous media by using experimental and theoretical research, which highlights the relationship between elastic waves and permeability during the propagation process. However, this theory cannot explain the dispersion and attenuation of elastic waves. In response to this problem, the BISQ and dual-porosity theories have been proposed. These two theories describe the local flow of fluid in an unevenly distributed porous medium. However, for such a dual-porosity medium with pores and cracks, the jet flow effect is quite notable, and Tang Xiaoming et al. (2011) examined this medium in detail and extended the self-consistent theory from the low- to the high-frequency band and proposed a unified theory of the elastic fluctuations in porous and fractured media.
According to the unified elastic theory of porous and fractured media, fast and slow P-waves and S-waves can be expressed as follows:

\[ k_p = \sqrt{\frac{1+b_1 \rho_f/\rho}{1-b_2/\rho_0}} \]  

\[ k_s = \omega \sqrt{\frac{\rho_s}{\mu}} \]  

In the equation, p and s represent P- and S-waves, respectively, and + and – indicate fast and slow, respectively. The parameters in equation (1) can be expressed as follows:

\[ b_{\pm} = \frac{1}{2} b_0 \left[ 1 \pm \sqrt{1 - 4 \alpha (1-c)/b_0} \right] \]  

\[ b_0 = -\beta (K_d + 4\mu/3 + \alpha^2 / \beta) / \alpha \]  

\[ k_{p0} = \omega \sqrt{(K + 4\mu/3) / \rho} \]  

\[ c = (\alpha - b_s/\rho_f b_0)/(\alpha + b_s) \]  

\[ b_s = \rho_f \theta \omega^2 \]

where \( \omega \) is the circular frequency, K is the bulk modulus of the water-saturated rock, \( K_d \) is the bulk modulus of the dry rock, \( \mu \) is the shear modulus, and \( \rho, \alpha \) and \( \beta \) in equation (2) can be expressed as follows:

\[ \rho = \rho_s (1-\varphi) + \rho_f \varphi \]  

\[ \alpha = 1 - K_d / K_s \]  

\[ \beta = \varphi / K_f + (\alpha - \varphi) / K_s \]

In the above equations, \( \rho_s \) is the density of the rock skeleton, \( \varphi \) is the rock porosity, \( K_s \) is the bulk modulus of the skeleton, \( \rho_f \) is the density of the pore fluid, and \( K_f \) is the bulk modulus of the fluid.

According to the study by Mavko et al. (1991), \( \mu \) in equation (2) can be obtained from the bulk modulus dispersion, expressed as follows:

\[ \frac{1}{\mu} - \frac{1}{\mu_0} = \frac{4}{15} \left( \frac{1}{K} - \frac{1}{K_0} \right) \]

where \( \mu_0 \) and \( K_0 \) are the bulk and shear moduli, respectively, in the absence of fluids in the cracks, which can be obtained according to the Gassmann theory. The bulk modulus of dry rock can be obtained from the following equation according to the OB theory:

\[ K_d = \frac{2(1+v)}{3(1-2v)} \mu_0 \]

where \( v \) is the Poisson ratio of the dry medium.

According to the Biot theory, the parameters related to pore fluids in equations (1) and (2) are:

\[ \hat{\rho} = \rho + \rho_f \omega^2 \theta \]  

\[ \theta = ik(\omega) / \eta \omega \]

The dynamic permeability \( k(\omega) \) in the equation is:

\[ k(\omega) = \frac{k_0}{\left[ 1 - \frac{i}{2} \tau k_0 \rho_f \omega / (\eta \phi) \right]^{1/2} - i k_0 \rho_f \omega / (\eta \phi)} \]

According to the modified coin theory, introducing the jet flow, in combination with the Biot-Gassmann theory, the rock modulus at an unknown saturation can be obtained as:

\[ K = K_d + \alpha^2 / \left[ (\alpha - \beta) / K_s + \varphi / K_f + S(\omega) \right] \]

\( S(\omega) \) in the equation above is the contribution of squeeze flow, which can be calculated as follows:
\[ S(\omega) = \frac{8}{3} \epsilon \frac{(1-\nu)}{\mu} f(\xi) \left[ \frac{1}{K_e} - \frac{1}{K_f} \right] \left[ \frac{1}{K_e} - \frac{1}{K_f} - f(\xi) \right] / \left[ 1 + \frac{4(1-\nu)K_f}{3\mu\gamma} \right] \left[ 1 - f(\xi) \right] \]  \tag{9}

where \( \epsilon \) is the fracture density, \( \gamma \) is the crack aspect ratio, and the frequency variation factor \( f \) and variable \( \xi \) can be expressed as:

\[
f(\xi) = \frac{2J_1(\xi)}{\xi J_0(\xi)}
\]

\[
\xi = \sqrt{\frac{3\pi \eta}{\gamma^2 K_f}}
\]  \tag{10}

The above equations describe the variation characteristics of the rock elastic parameters in the presence of squeezing jets in porous and fractured media. Tang Xiaoming and Su Yuanda et al. (2011) used the above research conclusions and analyzed gas-bearing sandstone reservoirs.

**Examples**

By using thin sections and mineral diffraction, for the X1 well in the study area, the average dolomite content was 75%, the limestone content was 18%, the mud amount was small, the crack density was 0.28, and the fracture aspect ratio was 0.0018. A gas-bearing reservoir identification template suitable for the study area was established by using pore and fracture models. As shown in Figure 2(a), the distribution of the samples with different water saturations is consistent with the simulation results. With increasing gas saturation, the sample points approach the gas line. Figure 2(b) shows the verified results of the actual well logging data of well X1. It can be seen from the figure that the reservoir data are basically distributed near the water line. Pilot production verification revealed that the reservoir is a water layer.

Through thin section and mineral diffraction experiments, for the X2 well in the study area, the average dolomite content is 82%, the limestone content is 9%, the mud amount is small, and the crack density is 0.22. The fracture aspect ratio is 0.0032. The gas-bearing reservoir identification template is established by using pore and crack models. Figure 3(a) shows the distribution of the experimental samples based on the established template. It can be seen from the figure that the distribution of the samples with different water saturations is consistent with the simulation results. Figure 3(b) shows the verified results of the actual logging data of the X2 well. It can be seen from the figure that the reservoir data are basically distributed near the gas line, and it is assessed as a high-quality reservoir. After pilot production verification, the layer is a gas layer with a daily gas production of 12256.6 m³.

Figure 2(a) X1 well experimental data verification; (b) X1 well actual logging data verification.
Figure 3 (a) X2 well experimental data verification; (b) X2 well actual logging data verification.

Conclusions

Based on acoustic experiments and the elastic theory of porous and fractured medium, this paper analyzes the acoustic velocity variation characteristics of gas-bearing carbonate reservoirs. The method of gas reservoir identification was examined, and the following conclusions were obtained:

(1) The lithology has a dominant effect on elastic wave propagation through porous and fractured media. For carbonate reservoirs, the gas-bearing reservoir identification template for different mineral compositions can be used to identify reservoirs by using porous and fractured medium models.
(2) This paper establishes a qualitative reservoir identification method through petrophysical experimental data and pore and crack models, and then uses acoustic logging data to quantitatively identify gas-bearing reservoirs, which provides a reliable basis for gas-bearing carbonate reservoir identification based on conventional logging data.

Acknowledgements

This research is financially supported by National Major Science and technology Project (2016zx05007-004; 2017ZX05009-001).

References


