Gas detecting of the Lower Permian dolomite reservoirs in Sichuan Basin using amplitude ratio attribute of PP-wave to PS-wave

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Abstract. At present, multi-wave multi-component seismic exploration has a good effect in the gas-bearing structural imaging improvement, fracture detection, clastic rock lithology description, reservoir monitoring, etc., but in gas detection, especially for the deep carbonate reservoir, there are not many successful cases. The paper takes the 5000m deep Lower Permian Qixia Formation dolomite gas reservoir in the central part of Sichuan Basin as the research target. Aiming at the differences in gas production characteristics of different wells and difficulty in gas detection, based on the high-precision matched 3D multi-wave seismic data by seismic processing and fine horizon interpretation of target formation, the differences between the PP- and PS-wave reflection amplitudes of high-production wells, low-production wells and poor gas wells are compared and analyzed, and multi-wave forward modelling and analysis are carried out. It is clear that the high production gas layer has the characteristics of strong PP-wave reflection and weaker PS-wave reflection. With the gas production decreasing from high to low, the reflection amplitude of PP gradually weakens, while that of PS change little and nearly have no obvious abnormalities. Finally, attribute of amplitude ratio of PP to PS were extracted for gas detection, which is in good agreement with the gas characteristics of the known wells and consistent with current geological understanding. The amplitude ratio attribute of PP to PS could provide a quick and reliable gas detection method for the deep dolomite reservoir.

1. Introduction

Multi-wave multi-component seismic exploration can obtain PP-wave of reflecting the skeleton and fluid and PS-wave (converted shear wave) of reflecting rock skeleton and anisotropy and combines the advantages of PP and PS wave exploration, thus facilitating the identification and characterization of complex reservoirs. Multi-wave exploration has been proven to get good effect in these aspects such as imaging below the “gas cloud”, target layer imaging of poor P-wave reflectivity, clastic lithology description, improving the resolution of shallow layer and characterization of fracture (ZHAO, 2008;
MA et al., 2010; WANG et al., 2012; WANG et al., 2017). It is generally believed that multi-wave exploration is likely to achieve better results in the future in fault imaging, density inversion, carbonate lithology description, fluid detection, and improving the deep resolution.

The degree of multi-wave seismic exploration in the central area of Sichuan Basin is relatively high. The results of exploration and development in recent years have shown that the Lower Permian deep marine carbonate natural gas resources in the area have great potential. Drilling results show that the gas production characteristics of different wells are different, which is characterized by the coexistence of high-production gas wells, low-production gas wells and poor gas wells. Aiming at the gas detection of the Lower Permian Qixia Formation, the advantages of multi-wave exploration are fully utilized to carry out detailed multi-wave horizon interpretation to improve the matching accuracy of PP-wave and PS-wave. On this basis, the reflection amplitude difference of PP-wave and PS-wave of different gas production wells are compared and analysed. Meanwhile, multi-wave forward analysis was carried out, finally it was clear that the high gas production layer has the characteristics of strong PP-wave reflection and weaker PS-wave reflection. Further, the amplitude ratio attribute of PP- and PS-wave were extracted, which get obvious effect on depicting the distribution of gas reservoir and show good agreement with gas characteristics of the known wells, and the amplitude ratio attribute of PP to PS-wave provide a quick and reliable gas detection method.

2. Geological background

The study area is located in the central part of Sichuan Basin in Western China, which has a flat surface and relatively simple underground structure. Multiple sets of formations produce gas and have high gas abundance. Based on the above factors, it is considered that this area is a very suitable test area for conducting multi-wave multi-component seismic exploration. The target layer is Qixia Formation of Lower Permian, which is between horizons of P1m and P1l in Figure1. The buried depth is 4500~5000m with lithology mainly limestone. The reservoirs are mainly porous dolomite reservoirs controlled by carbonate intraplatform sedimentary facies with thickness generally less than 15m and average porosity less than 5%. Drilling results show that the gas production in different wells are very different, which shows the coexistence of high production, low production and poor gas layer.

3. Fine matching of PP-wave and PS-wave

Data matching is the basis of multi-wave joint interpretation. Since the reflection coefficients of PP- and PS-wave on the interface are not the same, it is not necessary to correspond to PP- and PS-wave one-to-one. However, the main lithological interfaces are often similar, usually corresponding to seismic standard layer reflections. The standard layer reflections are used to fine calibrate and pick up the horizon, and then the PP- and PS-wave is time matched to improve the matching accuracy.

Figure 1 is the seismic section of PP-wave and PS-wave after matching. Figure 1b is the PS-wave matched only by the two horizons of P2l and P1l. It can be seen that the characteristics of PP- and PS-wave are basically the same, but in the local (the white arrow position), there is a deviation of about 10ms between PP-wave and PS-wave, which is intolerable and negligible for multi-wave joint interpretation, especially for thin layers. After matching with three horizons of P2l, P1m and P1l, the characteristics of PP- and PS-wave are more consistent, and the matching effect is significantly improved, which lays a good data foundation for the joint interpretation of PP- and PS-wave.
4. Logging and multi-wave seismic response characteristics of gas reservoirs

The gas production of different wells in the study area is quite different. Reservoir thickness of well W42 is 14.5m with daily gas production $22.42 \times 10^4$ m$^3$. And those of well W31 and W1 are 16.6m and 4m respectively with daily gas production $36.69 \times 10^4$ m$^3$ and $4.68 \times 10^4$ m$^3$. While well W41 has a reservoir thickness of only 3m, which is comprehensive interpreted as poor gas layer. Figure 2 is the logging characteristics and the P-impedance ($Z_p$)-S-impedance ($Z_s$) cross plot of Qixia Formation of well W42. The lithology of the gas layer is dolomite, which shows obvious high density, high S-wave impedance, and high P-wave impedance.

Figure 3 is PP- and PS-wave section crossing different wells. We can see that, for the high production gas wells (W42 and W31), PP-wave is strong reflection while PS-wave is almost weak reflection, but for the low production gas well (W1) and poor gas well (W41), the reflection of PP- and PS-wave are all weak. The above analysis shows that as the gas layer production goes from high to low, the corresponding PP-wave reflection gradually weakens, while the PS-wave changes less, that is, the change in the reflection strength of PP- and PS-wave may be closely related to the level of gas production.

5. Multi-wave seismic forward modelling
In view of the difference in the reflection characteristics of PP-wave and PS-wave under different gas conditions, the multi-wave seismic forward modelling is used for analysis. High production gas wells (W31) and poor gas well (W41) were selected and the Zoppeniz equation was used to conduct seismic forward modelling. The given angle of incidence is 1-40 degrees, which is close to the maximum incident angle of the target layer. The dominant frequency of ricker wavelet of PP and PS wave are 30Hz and 18Hz respectively, which are close to those of actual seismic data. Figure 4 and Figure 5 are the PP and PS wave forward modelling results of well W31 and W41 in depth domain. It can be seen from Figure 4 that the high production gas layer is strongly reflected on the angle gather and stack data of PP-wave, and has no obvious anomalies (weaker reflection) on the PS-wave. While the poor gas layer shows weaker reflection on that of PP-wave and no anomalies on the PS-wave (Figure 5). The seismic forward results are consistent with the feature of actual PP and PS seismic data (Figure 3). According to the theory of seismic wave propagation, when the formation is gas-bearing, the PP-wave attenuation is strong and prone to form abnormal reflections. However, the PS-wave is weakly attenuated and its response anomalous is less obvious because the shear wave (PS-wave) is mainly affected by the rock skeleton, while the influence of the pore fluid on it is weak. The PP- and PS-wave response characteristics of the two different gas bearing wells are consistent with the above basic theory.

6. Gas detection using amplitude ratio attribute of PP- and PS-wave

PP-wave is comprehensively affected by lithology and pore fluids. It is difficult to accurately determine the gas-bearing condition by only relying on the abnormal amplitude of the PP-wave. PS-wave (shear wave) is more affected by lithology and less affected by fluids. Combination of PP- and PS-wave is beneficial to reduce the ambiguity of the gas detection results and improve prediction accuracy.

According to the results of multi-wave forward modelling and the characteristics of the actual PP- and PS-wave seismic section, the high production gas layer has the characteristics of strong PP-wave reflection and weaker PS-wave reflection. Therefore, the amplitude attributes of PP- and PS-wave can be combined for gas-bearing detection. We extracted the maximum peak amplitude of the PP-wave (Figure 6a) and PS-wave (Figure 6b) in the target layer respectively, further calculated the amplitude ratio (Figure 6c). In Figure 6c, the high amplitude ratio area (red and yellow area) indicates favorable gas zone, which is consistent with current geological understanding. The high production gas wells (W31 and W42) are located in the region of higher amplitude ratio, and the low production gas wells (W1 and W11) and poor gas wells (W41, W207 and W16) are generally located in the lower amplitude ratio region. That is, the amplitude ratio of PP to PS can well distinguish the good gas layer from the bad gas layer. And this provide a quick and reliable gas detection method for the deep dolomite reservoir.
Figure 6. Maximum peak amplitude of PP-wave(a), PS-wave(b) and amplitude ratio of PP to PS (c) of the Qixia Formation.

7. Conclusions
Aiming at the gas detection of deep carbonate formation, based on the high-precision matched multi-wave data, by the analysis of well logging data, seismic response comparison and analysis of PP- and PS-wave and seismic forward modelling, we have a more reliable understanding on the multi-wave response characteristics of different gas-bearing conditions. That is, with the gas production decreasing from high to low, the reflection amplitude of PP-wave gradually weakens, while that of PS-wave change little and nearly have no obvious abnormalities. Finally, attribute of amplitude ratio of PP- and PS-wave were extracted for gas detection, and the gas detection results are in good agreement with the gas characteristics of the known wells and consistent with current geological understanding. The amplitude ratio of PP to PS provides a quick and reliable gas detection method for the deep dolomite reservoir.

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References
[1] ZHAO B.L. Application of multi-component seismic exploration in the exploration and production of lithologic gas reservoirs. Petroleum Exploration and Development, 2008, 35(4):397-409.
[2] MA Z.J., TANG J.M., XU T.J. Progress on multi-wave and multi-component seismic exploration. Progress in Exploration Geophysics, 2010, 33(3):247-253.
[3] WANG J.S., WANG X.B., YANG J., et al. Hydrocarbon prediction based on multi-wave data in Sanhu area. Oil Geophysical Prospecting, 2012, 47(4):605-609.
[4] WANG H.Q., GAO J.H., YANG W.Y., et al. Study on Identification of Carbonate Lithology Using Converted Wave Seismic Data, 79th EAGE Conference & Exhibition, 2017.