Carbonate fine lithology prediction using amplitude attribute of PS-wave

Chen Qiyan¹,², Wang Hongqiu¹,², Gao Jianhu¹ and Guo Xin¹

¹ Research Institute of Petroleum Exploration and Development-Northwest Petrochina, Lanzhou 730020, China
² State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu 610500, China

*Corresponding author’s e-mail address: chenqiyan@petrochina.com.cn

Abstract. The Lower Permian Maokou Formation and Qixia Formation in central part of Sichuan Basin have huge natural gas exploration potential. For the Maokou Formation, there is argillaceous limestone in the limestone background, and thin dolomite reservoirs are developed. The ability to use conventional PP-wave data to predict lithology and dolomite reservoirs is insufficient. In PP-wave seismic section, the response of argillaceous limestone and dolomite in the limestone background is not obvious, which limits the prediction accuracy of lithology. Making full use of high-precision matched PP-wave and PS-wave seismic data, we find a special phenomenon in the Maokou Formation that PP-wave usually shows weak amplitude and poor continuity while PS-wave shows stronger amplitude and better continuity. Aimed at the particular phenomenon, through multi-wave seismic forward modelling, log lithology interpretation, cross plot of P-impedance with S-impedance and seismic section comparison of PP-wave and PS-wave, it is clear that the weak peak of PP-wave and strong peak of PS-wave reflects weak and subtle change in lithology, which shows the existence of argillaceous limestone in limestone background. And the gas-bearing dolomite reservoirs are characterized by low frequency and weak amplitude on PP-wave, while show weak peak feature on PS-wave. Compared with PP-wave, the favorable lithology (dolomite) distribution predicted by maximum peak amplitude of PS-wave is more consistent with reservoir distribution and origin of hydrothermal-karst-controlled dolomite. Result of lithology prediction by PS-wave is reasonable and reliable for Maokou Formation.

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, so the special seismic exploration method is helpful for the identification and characterization of complex oil and gas 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; WANG et al., 2012; WANG et al., 2017).

The Lower Permian Maokou Formation and Qixia Formation in central part of Sichuan Basin have huge natural gas exploration potential. In recent years, many exploratory wells and appraisal wells have successively drilled high-production industrial gas flows in the dolomite pore-type reservoirs of the Qixia Formation and Maokou Formation. For Maokou Formation, there is argillaceous limestone
in the limestone background, and thin dolomite reservoirs are developed. The ability to use conventional PP-wave data to predict lithology and dolomite reservoirs is insufficient. In PP-wave section, response of argillaceous limestone and dolomite in the limestone background is not obvious, which limits the prediction accuracy of lithology. By analysis of multi-wave seismic data, we find a phenomenon that PP-wave shows weak amplitude and poor continuity while PS-wave stronger amplitude and better continuity. Aimed at the special phenomenon, by multi-wave modelling and lithology interpretation, it is probably determined that the amplitude difference between PP-wave and PS-wave is a reflection of subtle lithology change (argillaceous limestone in the limestone background). The lithologic interface is further confirmed by the comparison of PP-wave and PS-wave. According to the multi-wave seismic response analysis of the gas-producing well, the gas-bearing dolomite reservoir is characterized by low frequency and weak amplitude on PP-wave, while weak peak feature on PS-wave. Finally, we use maximum peak amplitude of PS-wave for fine lithology prediction. Compared with PP-wave, the favorable lithology (dolomite) distribution predicted by maximum peak amplitude of PS-wave is more consistent with reservoir distribution and origin of hydrothermal-karst-controlled dolomite, which shows obvious advantage of PS-wave data in fine lithology identification.

2. Geologic background and basic feature of multi-wave seismic data
The study area is located in the central part of Sichuan Basin in Western China. Target layer is Maokou Formation of Lower Permian, which is presented between horizons P2l and P1m in Figure 1. The target’s buried depth is about 4500m with lithology mainly limestone. The reservoir is mainly hydrothermal-karst-controlled dolomite pore reservoir with thickness less than 20m and porosity less than 5%. Figure 1 is the fine-matched PP-wave and PS-wave crossing wells, and its plane position is shown as line AB in Figure 4. The main frequency of the target layer is 30Hz and 24Hz respectively for PP-wave and PS-wave. It can be seen in Figure 1 that both PP-wave and PS-wave have clear imaging, high signal-to-noise ratio and good consistency, which benefits the subsequent multi-wave joint interpretation.

In Figure 1, it’s easy to see that the reflection of Maokou Formation is weak in PP-wave but obviously strong and continuous in PS-wave. For the difference in reflection intensity of PP-wave and PS-wave, we carried out comprehensive analysis by multi-wave seismic forward modelling, well log lithology interpretation and careful comparison and analysis of multi-wave seismic data.

![Figure 1. Seismic section of PP-wave and PS-wave crossing wells M1, M2, M3 and M4.](image)

3. Research method
Here we select well M1 as the study object, which has reliable logging data. The Zuppeniz equation is used to perform the wave field modelling and 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-wave and PS-wave are given both 28Hz, which are close to that of actual multi-wave seismic data. Figure 2(a) and Figure 2(b) show the depth domain results of multi-wave modelling. The left log curves are respectively Vp (P-wave velocity), Vs (S-wave velocity) and density. The middle is angle gather of modelling and the right is stack result. It can be seen from the modelling results that PP-wave shows weak reflection while PS-wave obvious strong reflection.
For reasonably interpretation the reflection characteristics difference between PP-wave and PS-wave, first we analyse the logging curve of Vp and Vs. Seen from the log curve, the variation range of Vp in target layer (the black dotted box) is small but that of Vs is larger, thus this causes the phenomenon that PP-wave weak reflection and PS-wave strong reflection. Also, the modelling result of well M1 is basically consistent with the actual multi-wave seismic response in Figure 1.

In addition, we use the logging and seismic data for comprehensive interpretation. Figure 2c is the lithology interpretation result of target layer in well M1. We can see that the lithology of Maokou Formation is mainly limestone, and the GR value is higher than the surrounding pure limestone formation near depth of 4320m, also having the feature that Vp and Vs reducing and variation range of Vs greater than that of Vp. By comprehensive analysis of well logging data, it is interpreted to be argillaceous limestone, which shows subtle changes of clay content relative to pure limestone. The location of lithological change just correspond to the position that PP-wave showing weak reflection and PS-wave showing strong reflection, which reveals that the S-wave or PS-wave is better for identification of weak and subtle carbonate lithology change than traditional PP-wave, and this is also consistent with the propagation mechanism of P-wave and S-wave.

Further, by analysing the seismic section of PP-wave and PS-wave crossing wells (Figure 1), we can see that the phenomenon of PP-wave weak peak and PS-wave strong peak in the target layer is prevalent, so we further determine the above phenomenon is response of subtle lithology change (argillaceous limestone in limestone background). Result of lithology interpretation about the adjacent well M2 and M3 is consistent with well M1, which showing characteristic of argillaceous limestone in limestone background.

![Figure 2. Modelling result of PP (a), PS (b) and lithology interpretation of well M1.](image)

It is worth noting that target layer of well M4 shows low frequency and weak amplitude feature on PP-wave but weak peak amplitude on PS-wave (Figure 1), which can be better explained based on reservoir and fluid characteristics, also can be explained by log interpretation result and cross plot of P-impedance with S-impedance (Figure 3). Lithology of reservoir in well M4 is dolomite, having obviously high density and high S-impedance (Figure 3), and the reservoir thickness is 20.3m with daily gas production 24.7×10⁴m³. Due to weak P-impedance difference between dolomite and limestone (Figure 3b) and gas-induced high frequency attenuation, the PP-wave shows low-frequency weak amplitude feature (Figure 1). In addition, S-impedance difference between dolomite and limestone is larger than that of P-impedance (Figure 3b). As the PS-wave is mainly affected by lithology, when the lithology interface changing from argillaceous limestone-limestone to dolomite-limestone, the corresponding response of PS-wave just changes from strong peak to weak peak.

Based on the above analysis, it can be concluded that the strong peak of Maokou Formation on PS-wave is closely related to argillaceous limestone, and the weak peak is related to dolomite, which is just the lithology of favorable reservoirs we are interested.
Figure 3. Log comprehensive interpretation result (a) and cross plot of P-impedance with S-impedance (b) of Maokou Formation in well M4.

4. Application effect

Figure 4 are attribute map overlay with interpreted faults overlay (black line). Based on above analysis results, the maximum peak amplitude of PP-wave (Figure 4a) and PS-wave (Figure 4b) in Maokou Formation are extracted. In Figure 4a and 4b, the purple and blue represent high value of amplitude, corresponding to the strong wave reflection on the seismic section, which indicating unfavorable lithology (argillaceous limestone), while the red and yellow represent relative low value of amplitude, which corresponding to the weak reflection of the seismic section and indicating the favorable lithology (dolomite). The biggest difference between Figure 4a and Figure 4b is in the north and middle region. To analyse the difference, take seismic section through line CD in Figure 4 for example, it can be seen that PP-wave show as wide trough while PS-wave strong peak, as shown by the arrows in Figure 5.

Figure 4c shows the reservoir distribution of Maokou Formation predicted by the frequency attenuation attribute. The high value area (red and yellow) indicates distribution area of favorable reservoirs and the low value area (light blue) indicates unfavorable reservoirs. Obviously, the favorable lithology (dolomite) depicted in Figure 4b is more consistent with favorable reservoir than that of Figure 4a. It is worth noting that the distribution of favorable lithology (dolomite) depicted in Figure 4b have a good relationship with the distribution of faults, which is quite consistent with origin of hydrothermal-karst-controlled dolomite. Based on the above analysis, it can be concluded that the lithology prediction by the PS-wave is more reasonable and more reliable than that of the conventional PP-wave.

Figure 4. Maximum peak amplitude of PP-wave (a) and PS-wave (b) of Maokou Formation and the reservoir distribution predicted by the frequency attenuation attribute (c).
Figure 5. PP-wave section(a) and PS-wave section(b) through line CD

5. Conclusions

Through multi-wave seismic forward modelling, combined with log lithology interpretation, cross plot of P-impedance with S-impedance and seismic section comparison of PP and PS, it is clear that the weak peak of PP-wave and strong peak of PS-wave in Maokou Formation reflects weak and subtle change in lithology, which shows the existence of argillaceous limestone in limestone background. And the gas-bearing dolomite reservoirs are characterized by low frequency and weak amplitude on PP-wave, while shows weak peak feature on PS-wave. Compared with PP-wave, the favorable lithology (dolomite) distribution predicted by maximum peak amplitude of PS-wave is more consistent with reservoir distribution and origin of hydrothermal-karst-controlled dolomite. The result of lithology prediction by PS-wave is reasonable and reliable for Maokou Formation.

Acknowledgments

Thanks for the supports of the National Science and Technology Major Project of China (2016ZX05007006) and the Science and Technology Project of Petrochina (2019B-0607).

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] 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.
[3] 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.