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Graded and Quantitative Technology and Application of Coal-Bearing Reservoir Based on Seismic Reflection Characteristics

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Abstract

Taiyuan formation is the main exploration strata in Ordos Basin, and coals are widely developed. Due to the interference of strong reflection of coals, we can not completely identify the effective reservoir information of coal-bearing reservoir on seismic data. Previous researchers have studied the reservoir by stripping or weakening the strong reflection, but it is difficult to determine the effectiveness of the remaining reflection seismic data. In this paper, through the establishment of 2D forward model of coal-bearing strata, the corresponding geophysical characteristics of different reflection types of coal-bearing strata are analyzed, and then the favorable sedimentary facies zones for reservoir development are predicted. On this basis, combined with seismic properties, the coal-bearing reservoir is quantitatively characterized by seismic inversion. The above research shows that the Taiyuan formation in LS block of Ordos Basin is affected by coals and forms three or two peaks in different locations. The reservoir plane sedimentary facies zone is effectively characterized by seismic reflection structure. Based on the characteristics of sedimentary facies belt and petrophysical analysis, the reservoir is semi quantitatively characterized by attribute analysis and waveform indication, and quantitatively characterized by pre stack geostatistical inversion. Based on the forward analysis of coal measure strata, this technology characterizes the reservoir facies belt through seismic reflection characteristics, and describes coal measure reservoirs step by step. It effectively guides the exploration of LS block in Ordos Basin, and has achieved good practical application effect.

Keywords

Coal-Bearing Reservoir, Seismic Reflection Characteristics, Waveform Indication Inversion, Geostatistics Inversion

1. Introduction

Strong amplitude characteristics are common in seismic data. Widely distributed caprocks, turbidite development areas, calcareous strata, and stable coal seam development zones all exhibit strong amplitude characteristics in seismic data. Due to the shielding characteristics of strong reflections, reservoir prediction is very difficult (Wu, 2019; Lai et al., 2015; Liang et al., 2019). Generally speaking, compared with other clastic rocks, coal seams are interlayers with low-speed and low-density characteristics, and their wave impedance differs significantly from that of surrounding rocks. The reflected waves formed are stable, have strong energy, and have good continuity, making them easy to track on seismic data (Gao et al., 2002; Zhang et al., 2016; Du et al., 2016). The top and bottom interfaces of a single coal seam will form strong reflection interfaces. Due to the limitations of coal seam thickness and seismic vertical resolution, the top and bottom waves of a single coal seam are generally indistinguishable, ultimately forming composite reflection characteristics (Du et al., 2016; Zhang, 2016). Due to the shielding effect of coal seams, seismic data in the middle and lower parts of coal seams have weak energy and poor continuity, making it difficult to solve geological problems such as reservoir prediction under and between coal seams.

A large amount of research has been conducted on the seismic reflection characteristics and effectiveness of coal seams by previous researchers. Gochioco defined coal seam reflection as a strong thin layer reflection (Gochioco, 2012); Widess studied the vertical resolution of seismic data and transformed the definition of thin layers from qualitative to quantitative, defining thin layers as media thickness less than 1/4 of the main wavelength (Widess, 1973); Koefoed used forward modeling to analyze the relationship between thin layers and composite waves (Koefoed & De Voogd, 1980); Farr defined the detectability of coal seam earthquakes (Farr, 1977); Tang Wenbang and others believe that the key to whether a thin layer (single coal seam) can be detected is whether its reflected waves can be distinguished from the background reflection (Tang et al., 2012). Many scholars at home and abroad study the characterization of sand bodies under strong coal seam reflection by weakening the amplitude of coal seam reflection. Mallat and others apply matching tracking algorithms to adaptively decompose seismic signals, match coal seam reflection signals, and retain their effective reflections (Mallat & Zhang, 1993). Many domestic scholars use methods such as wavelet decomposition and reconstruction, matching tracking, wavelet transform, generalized S-transform, and compression sensing signal decomposition and reconstruction to peel off and weaken strong reflections in coal seams (Li et al., 2014b; Zhang et al., 2012; Li et al., 2014a; He et al., 2019; Chen et al., 2016). Meanwhile, previous researchers have attempted to strip and weaken strong coal seams using different methods, but most of them rely mainly on mathematical algorithms, making it difficult to prove the geophysical reliability of residual reflection amplitudes, thus limiting the application and promotion of many methods (Wu, 2019).

Based on the development characteristics of coal seams and reservoir distribution in the LS block of Ordos, this article establishes forward models for vertical combinations of different coal bearing strata, analyzes the spatial distribution characteristics of different reflection types in coal bearing strata, and predicts the spatial distribution types of reservoirs; On this basis, combining seismic inversion and seismic attribute analysis, classify and quantitatively characterize coal bearing reservoirs. The reservoir prediction method based on coal seam seismic reflection formed by this achievement has guided the optimization and target evaluation of favorable areas in the LS block of the Ordos Basin, providing a large amount of evidence for well deployment and adjustment.

2. Regional Geological Overview

The Ordos Basin is known as a "full basin of gas and half basin of oil" and is an important large-scale oil and gas basin in China. Multiple large gas fields have been discovered in the basin, such as Sulige, Daniudi, Yulin, Wushenqi, etc. Significant breakthroughs and progress have been made in the exploration of unconventional oil and gas fields such as tight gas and tight oil, and there is still great exploration potential (Mi & Zhu, 2021). The Ordos Basin is a cratonic basin consisting of a Paleozoic platform and marginal depression, as well as a Mesozoic and Cenozoic intra platform depression (Du et al., 2021). It covers an area of approximately 24×10^4 km^2 and can be further divided into six primary structural units: the Yimeng Uplift, the Shaanbei Slope, the Jinxi Fold Belt, the western margin thrust fault zone, the Tianhuan Depression, and the Weibei Uplift (**Figure 1**). The LS block is located at the junction of the Yishan Slope and the Jinxi Fold Belt. The strata mainly develop from old to new, including the Ordovician, Carboniferous, Permian, Triassic, Jurassic, Cretaceous, Neogene, and Quaternary (Cao et al., 2018). The Taiyuan Formation is distributed throughout the entire basin, mainly consisting of gray white medium to coarse grained quartz sandstone and deep gray coarse grained lithic quartz sandstone. A stable and highly continuous thick coal seam with a thickness of about 3-10m is developed at the bottom, and several sets of thin coal seams with uneven thickness and weak continuity are developed in the middle. This article mainly focuses on the quantitative characterization of reservoir classification under the influence of coal seams in the Taiyuan Formation of the Permian (**Figure 2**). Based on the geological and sedimentary understanding of LS area, improve the reasonable geophysical prediction methods and ideas for coal bearing reservoirs.

The Taiyuan Formation is a key production layer of tight gas in the LS block, and the quantitative characterization of its coal bearing reservoirs is a crucial issue that must be taken seriously in the exploration and development of this area. The Taiyuan Formation mainly develops two sets of coal seams, and there are strong reflection characteristics caused by coal seams during earthquakes, which

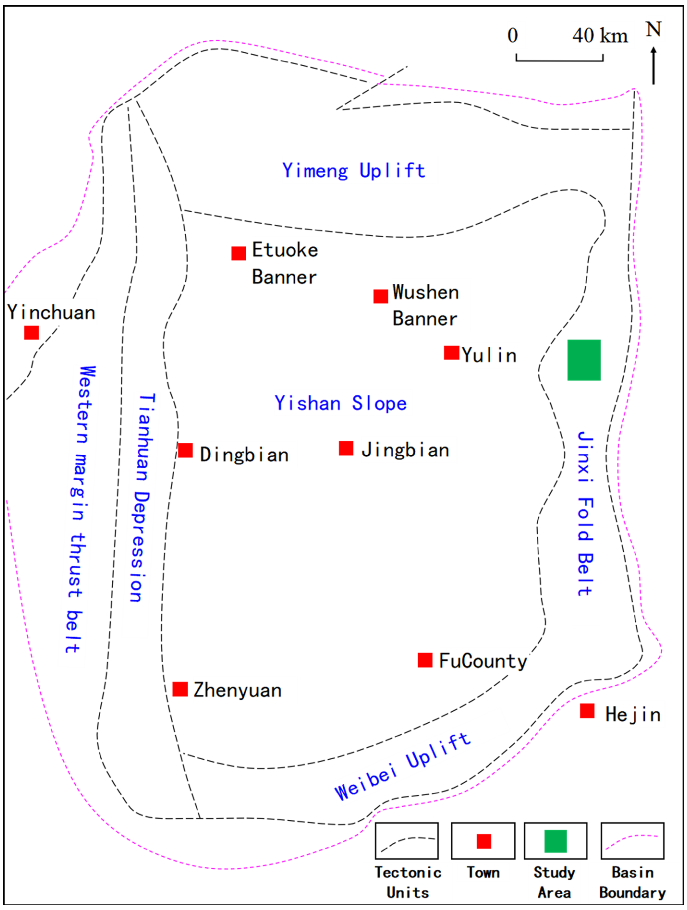


Figure 1. Structural division of ordos basin.

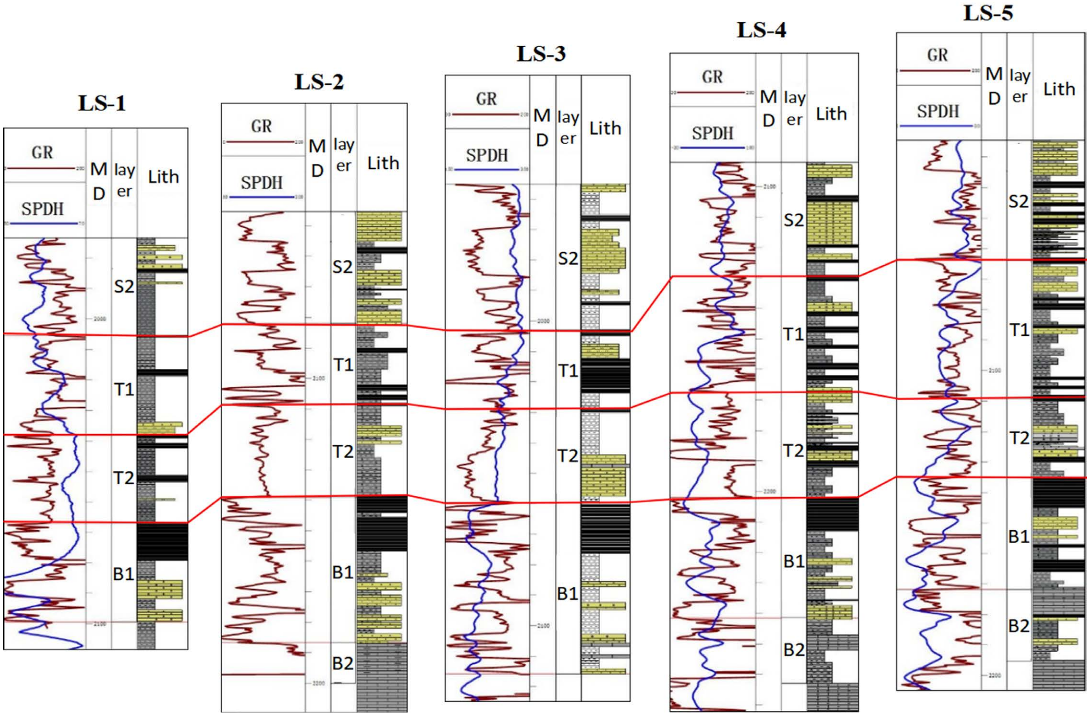


Figure 2. Stratigraphic correlation of Taiyuan formation of LS block.

mask the relevant information of reservoirs between and under coal. Research on geophysical reservoir prediction and geological interpretation also needs further improvement. The Taiyuan Formation in the LS block has strong reflection amplitude energy and continuity, and the seismic coaxial axis exhibits lateral bifurcation and merging phenomena. The number of reflections also varies, manifested as different reflection characteristics of bimodal or triple peaks (**Figure 3**). Without amplitude decomposition and weakening, the thickness of sandstone and coal seams, as well as the spacing between two sets of coal seams in the logging interpretation results, are statistically analyzed to identify the geological reasons for seismic co axial bifurcation and merging of typical reflection characteristics. By utilizing the sand coal combination relationship with different reflection characteristics, favorable sedimentary facies zones are predicted through seismic structural analysis. Based on the characteristics of sedimentary facies zones and rock physical analysis, coal bearing reservoirs are classified and quantitatively characterized through seismic inversion and other methods.

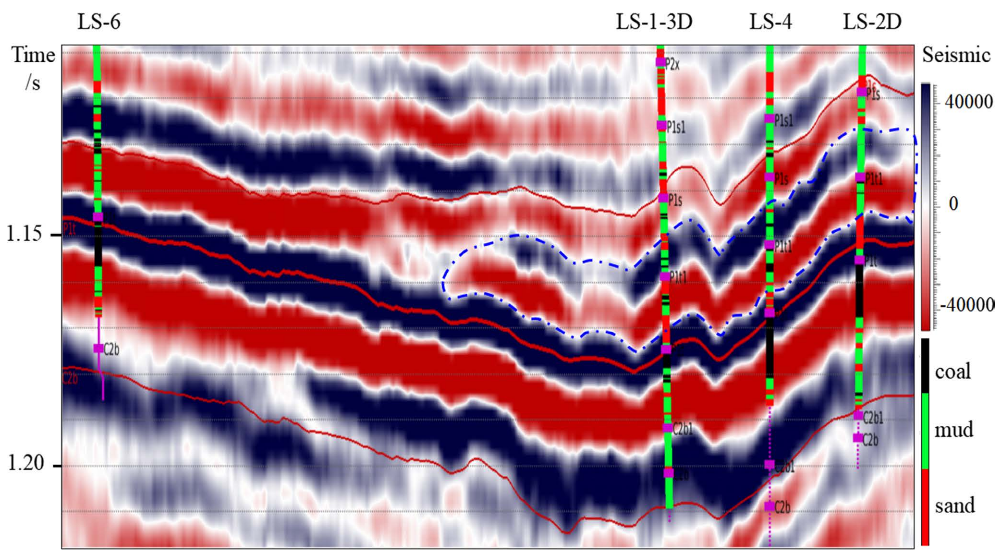


Figure 3. Seismic profile of LS block in Ordos basin.

3. Forward Simulation of Coal Bearing Reservoirs

Structural movement, reflection of special lithological bodies, and changes in lithology can all cause changes in seismic co axial bifurcation and merging (Chen & Chen, 2019). The occurrence of the Carboniferous and Permian strata in the LS block of the Ordos Basin is stable, and the dip angle of the strata changes relatively little. Structural movement and special lithological bodies are not the main factors causing changes in seismic reflection characteristics. The impedance difference between tight sandstone and mudstone in the LS block is small, and can be considered as a unified surrounding rock background compared to coal seams. The tuning effect between the continuously developed coal seams at the bottom of the Taiyuan Formation and the internal coal seams of the Taiyuan Formation can cause changes in the seismic coaxial axis. This wave group characteristic is manifested as a three peak or two peak feature on the seismic profile (**Figure 3**). In order to study the relationship between the seismic response characteristics of coal bearing reservoirs and the development of coal seams, this study will select the thickness of the bottom coal seam of the Taiyuan Formation, the thickness of the middle coal seam of the Taiyuan Formation, and the distance between these two sets of coal seams for intersection. Analysis shows that the bimodal and three peak seismic reflection characteristics are closely related to the spacing between coal seams.

In order to study the relationship between the reflection characteristics of coal bearing reservoirs and coal seams, combined with previous research results (Wu, 2019), a forward model was established based on logging data and seismic data (**Figure 4**). The forward model includes the following parameters: the overall thickness of the Taiyuan Formation is about 90 - 110 meters, there are two sets of coal seams in the Taiyuan Formation, and a stable and thick coal seam at the bottom of the Taiyuan Formation, about 6 - 14 meters; According to the actual situation, set up the second set of coal seams in the middle of Taiyuan Formation, with a thickness of about 3 - 11 meters, and the distance between the two sets of coal seams varies between 5 - 20 meters; The coal seam velocity is set at 2375 m/s and the density is 1.35 g/cm^3; According to the average elastic parameters of the selected typical wells, the velocity of the Benxi Formation is 4900 m/s and the density is 2.589 g/cm^3; The velocity of the Taiyuan Formation is 4424 m/s with a density of 2.576 g/cm^3, while the velocity of the Shanxi Formation is 4293 m/s with a density of 2.478 g/cm^3; According to the frequency spectrum analysis of seismic data, the wavelet is set as a positive polarity Ricker wavelet at 27 Hz. From the seismic response corresponding to the forward model (**Figure 4**), it can be seen that when the distance between the coal seams inside the Taiyuan Formation and the bottom coal seam is large, a three peak reflection feature will appear, while when the distance between the coal seams is small, a two peak reflection feature will appear. At the same time, we can see that the relationship between the seismic reflection feature and the thickness of the coal seams in this area is relatively small, and overall, it is greatly affected by the distance between the coal seams.

4. Quantitative Characterization of Coal Bearing Reservoir Classification

According to the forward modeling results above, the seismic waveform characteristics are related to the coal seam spacing, and the coal seam spacing in the three peak area is relatively large. The terrain of the coal swamp is generally gentle, and the distance between the two main coal seams increases, indicating that there is a geological subsidence process after the sedimentation of the lower coal seams, which is more likely to form sedimentary microfacies with tidal channels, river channels, and other sand bodies. Based on this, the number of seismic reflection waves is counted to characterize the sedimentary characteristics of the LS block in the Ordos Basin. According to **Figure 4**, it can be seen that the reservoir

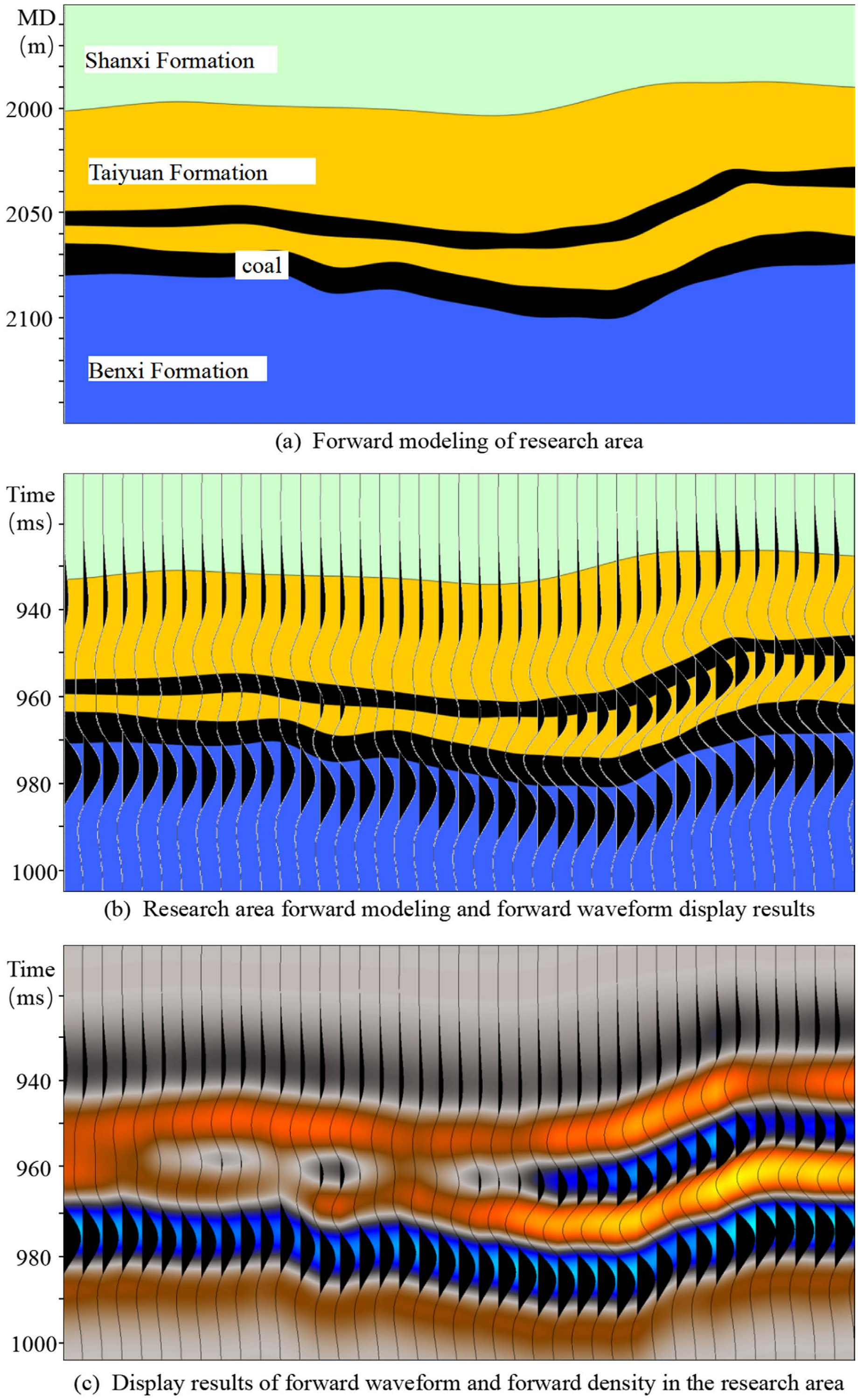


Figure 4. Forward modeling and results of LS block.

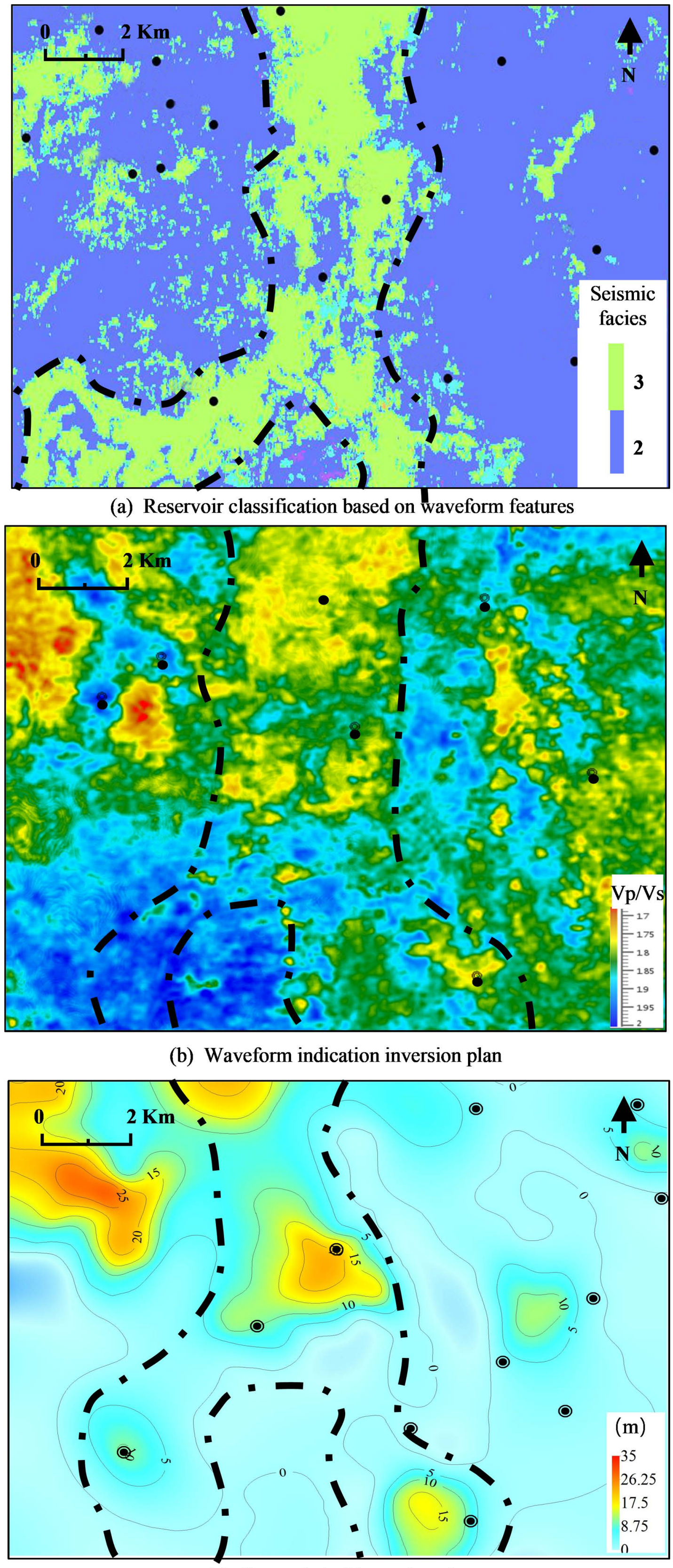
classification method based on seismic reflection structure has good adaptability to the sand bodies developed in the central part of the study area, and can provide a preliminary description of the distribution of coal bearing reservoirs. On this basis, based on the seismic response logging forward modeling and rock physics analysis of reservoir thickness, the feasibility of reservoir inversion is demonstrated, indicating that elastic parameters such as longitudinal and transverse wave velocity ratio and longitudinal wave impedance have certain resolution ability for tight reservoirs in this area. Based on the advantages of different reservoir prediction methods integrated into tight coal bearing reservoirs, a comprehensive classification and quantitative judgment of the spatial distribution characteristics of reservoirs is carried out.

The characteristics of seismic waveforms can often reflect changes in the reservoir. Under the strong reflection influence of coal seams, subtle changes in waveforms that cannot be directly recognized can also be caused by changes in coal seams and reservoirs below coal seams. Especially in areas with stable strata and relatively stable coal seam development, these subtle waveform changes can also indicate changes in reservoirs (Chen et al., 2020; Yue & Qian, 2020; Wang, 2019). The dip angle of the LS block is relatively small, and the development of coal seams in the lower part of the Taiyuan Formation is relatively stable. Through waveform inversion, the lateral variation characteristics of earthquakes can be fully utilized to semi quantitatively characterize coal bearing reservoirs. Through the above research, a qualitative and semi quantitative understanding of the development characteristics of the LS block reservoir has been obtained. Based on this, the advantage of high-resolution logging data is considered, and the geostatistical inversion based on Markov chain Monte Carlo algorithm is used (Yuan et al., 2016; Haas & Dubrule, 1994; Dubrule et al., 1998; Cooke & Schneider, 1983; Li et al., 2020). Combined with the lateral resolution of seismic data, the vertical resolution is improved to quantitatively predict coal bearing reservoirs (**Figure 5**).

The unconventional tight sandstone reservoir prediction technology formed through research has been applied in the preliminary research and drilling process of reservoirs in the Linxing Shenfu gas fields. Good results have been achieved in the actual drilling process. Among them, the X-H well has completed drilling at a depth of 3167.00 m (measured depth)/2172.57m (vertical depth), and encountered a horizontal section length of 640 meters. According to logging data, this well has encountered a total of 316.5 m/11 gas layers, 85m/6 poor gas layers, and 238.5 m/11 dry layers, The cumulative length of sandstone drilling is 640 m, with a drilling rate of 62.7% for gas layers and poor gas layers, and a drilling rate of 100% for sandstone. After pressing, there is no obstruction of 90,000 cubic meters per day.

5. Conclusion

1) This study establishes seismic response characteristics of forward modeling, analyzes the constructive effect of the relationship between coal bearing reservoir sand bodies and coal seams on seismic waveforms, and characterizes favorable sedimentary facies zones; On this basis, the waveform characteristics of earthquakes are used for semi quantitative reservoir prediction, and then



(a) Reservoir classification based on waveform features

(b) Waveform indication inversion plan

(c) Geostatistical inversion plan

Figure 5. Plane characterization of coal measures reservoir of LS block.

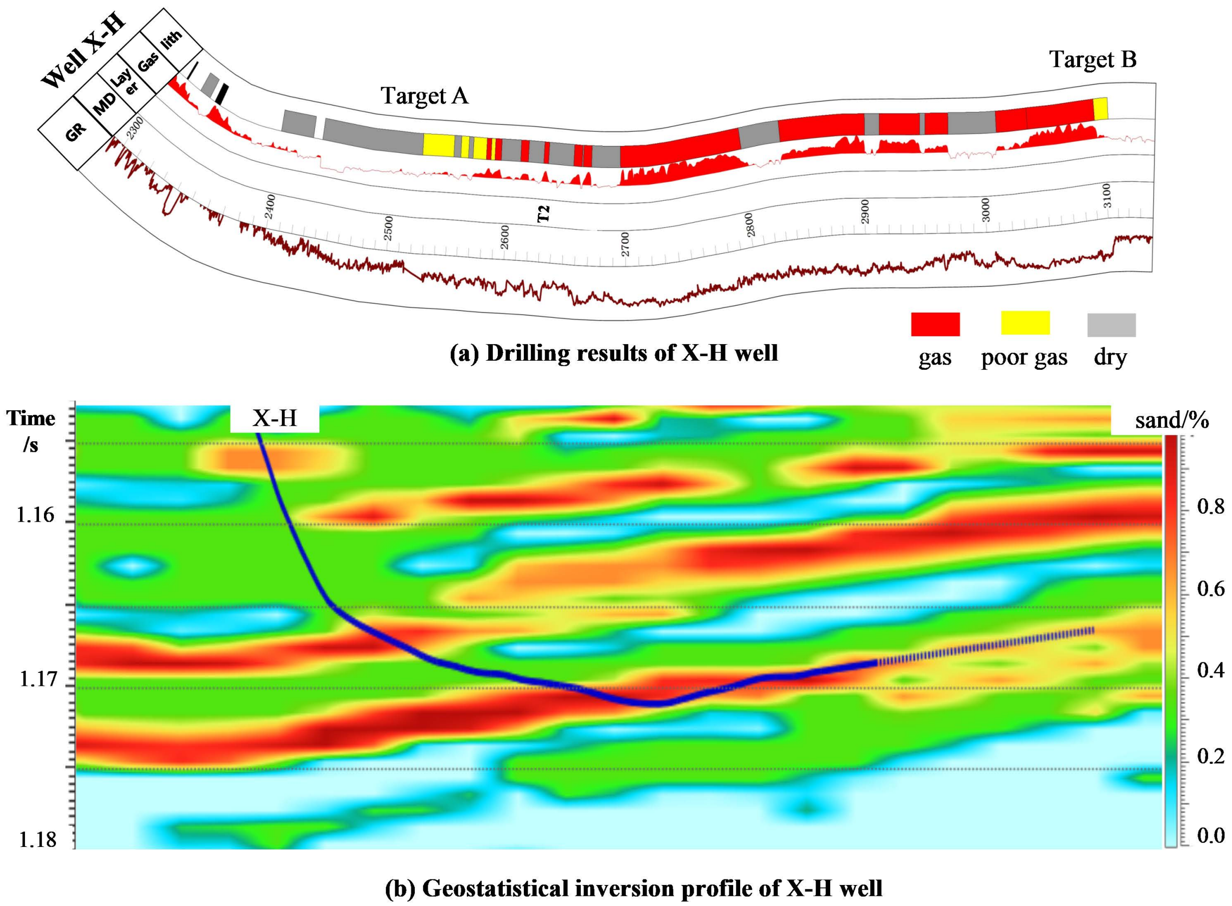


Figure 6. Comparison diagram of drilling and inversion of X-H well.

combined with high-resolution logging and geostatistical inversion methods, the reservoir is quantitatively characterized. The application in the LS block of the Ordos Basin has achieved good results.

2) The LS block in the Ordos Basin is affected by strong coal seam reflections, making it difficult to predict coal bearing reservoirs and may not achieve the expected results during well deployment. The application of classification and quantitative characterization technology for tight coal bearing reservoirs in the LS block has achieved a prediction accuracy rate of over 80%, significantly improving the accuracy of coal bearing reservoir prediction. At the same time, the deployment of well locations has better daily gas production, improving the productivity and efficiency of coal bearing reservoirs.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Cao, D. Y., Nie, J., Wang, A. M., Zhang, S. R., & Zhang, B. (2018). Structural and Thermal Control of Enrichment Conditions of Coal Measure Gases in Linxing Block of Eastern Ordos Basin. *Journal of China Coal Society, 43,* 1526-1532.

Chen, Y. H. et al. (2020). A Method of Seismic Meme Inversion and Its Application. *Oil Exploration and Development: English Version, No. 6,* 1235-1245. https://doi.org/10.1016/S1876-3804(20)60132-5

Chen, Y. H., & Chen, J. (2019). The Application of Seismic Meme Inversion to Thin Sand Distribution Prediction under Coal Shield. *Geophysical and Geochemical Exploration, 43,* 1254-1261.

Chen, Z. G., Liu, L. S., Liu, Y. Q., Bi, L. T., Shang, A. H., & Xu, F. (2016). Thin-Sandstone Reservoir Prediction in Coal-Bearing Strata. *Oil Geophysical Prospecting, 51,* 52-57+6.

Cooke, D. A., & Schneider, W. A. (1983). Generalized Linear Inversion of Reflection Seismic Data. *Geophysics, 48,* 665. https://doi.org/10.1190/1.1441497

Du, J., Zhu, G. H., Wu, L. F., Zhang, Z. H., Gao, J. X., Yu, Y. J., Ma, Z. J., & Zhang, M. (2021). "Multi-Series and Quasi-Continuous" Tight Gas Accumulation Pattern and Giant Gas Field Exploration Practice in Linxing Area. *Natural Gas Industry, 41,* 58-71.

Du, Y. S., Fan, T. T., Zhang, J. H., Zhang, Z. J., & Liu, L. (2016). Seismic Description Technology of Deep Reservoirs above Coal Seams: A Case Study of Xishanyao Formation in Yongjin Oilfield. *Progress in Geophysics, 31,* 1562-1568. https://doi.org/10.1088/1475-7516/2016/04/020

Dubrule, O., Thibaut, M., Lamy, P., & Haas, A. (1998). Geostatistical Reservoir Characterization Constrained by 3D Seismic Data. *Petroleum Geoscience, 4,* 121-128. https://doi.org/10.1144/petgeo.4.2.121

Farr, J. (1977). High-Resolution Seismic Methods Improve Stratigraphic Exploration. *Oil & Gas Journal, 75,* 182-188.

Gao, Y., Zhang, Q. H., Chen, C. W., & Zhang, D. M. (2002). Applied Research on 3D Seismic Exploration in a Thin Coal Seam under the Shield of Strong Reflection Layer. *Journal of Shandong University of Science and Technology (Natural Science), No. 1,* 54-58.

Gochioco, L. M. (2012). Modeling Studies of Interference Reflections in Thin-Layered Media Bounded by Coal Seams. *Society of Exploration Geophysicists, 57,* 1209-1216. https://doi.org/10.1190/1.1443336

Haas, A., & Dubrule, O. (1994). Geostatistical Inversion: A Sequential Method of Stochastic Reservoir Modeling Constrained by Seismic Data. *First Break, 12,* 561-569. https://doi.org/10.3997/1365-2397.1994034

He, F., Weng, B., Han, G., Ding, J. C., & Tian, Y. X. (2019). A Seismic Constraint-Based Technology for Elimination of Strong Coal Seam Reflection via Well-Control and Matching Pursuit. *China Offshore Oil and Gas, 31,* 61-66.

Koefoed, O., & De Voogd, N. (1980). The Linear Properties of Thin Layers, with an Application to Synthetic Seismograms over Coal Seams. *Geophysics, 45,* 1254-1268. https://doi.org/10.1190/1.1441122

Lai, S. H., Liang, Q. S., Zeng, H. L., & Li, P. F. (2015). Influences of Coal Seam on Seismic

Reflection Characteristics of Sand and Significances of Seismic Lithology: A Case Study of Shan-2 Member in Ordos Basin. *Oil Geophysical Prospecting, 50,* 136-143+18.

Li, B. Y., Huang, X., Wang, W., Li, W. J., & Tu, Q. C. (2020). High-Resolution Channel Identification and Thin Bed Prediction Based on Pre-Stack Geostatistics Inversion: A Case Study of B Gas Field in the East China Sea. *Chinese Journal of Engineering Geophysics, 17,* 236-241.

Li, H. S., Yang, W. Y., Tian, J., & Wu, G. C. (2014a). Coal Seam Strong Reflection Separation with Matching Pursuit. *Oil Geophysical Prospecting, 49,* 866-870+818.

Li, Z. J., Liu, Q., Li, H. Y., Tang, W. B., & Yao, Y. (2014b). Application of HFC Technique for Hydrocarbon Identification in Fracture-Cave Reservoirs of Lower-Ordovician Carbonate in Tahe Oil Feild. *Geophysical Prospecting for Petroleum, 53,* 484-490.

Liang, J., Chen, W., Luo, M., Luo, Z., & Liu, P. (2019). Application of Seismic Motion Inversion in Thin Layer Prediction of a Oilfield in Pearl River Mouth Basin. *Computing Techniques for Geophysical and Geochemical Exploration, 41,* 327-333.

Mallat, S., & Zhang, Z. (1993). Matching Pursuits with Time-Frequency Dictionaries. *IEEE Transactions on Signal Processing, 41,* 3397-3415. https://doi.org/10.1109/78.258082

Mi, L. J., & Zhu, G. H. (2021). Geological Characteristics and Exploration Breakthrough in Linxing-Shenfu Tight Gas Field, Northeastern Ordos Basin. *China Petroleum Exploration, 26,* 53-67.

Tang, W. B., Liu, L. X., Fan, J. F., & Yao, Y. (2012). Research on Seismic Detectable Resolution. Research on Seismic Detectable Resolution. *GPP, 51,* 107-118+103.

Wang, Y. J. (2019). Application of Seismic Motion Inversion in the Third Member of the Shahejie Formation in the Northeastern Kenli. *Journal of Physics: Conference Series, 1176,* Article ID: 042078. https://doi.org/10.1088/1742-6596/1176/4/042078

Widess, M. B. (1973). How Thin Is a Thin Bed? *Society of Exploration Geophysicists, 38,* 1176-1180. https://doi.org/10.1190/1.1440403

Wu, X. C. (2019). *Geological Interpretation and Hydrocarbondetection Related to the Paleozoic Coal-Bearing Series Reflections in the Ordos Basin: A Case Study of the Eastern Region of the South Section of Hangjinqi*. Ph.D. Thesis, Northwest University.

Yuan, C. Y., Jia, J. L., & Zhang, H. (2016). The Application of Geological Statistics to Reservoir Prediction. *Chinese Journal of Engineering Geophysics, 13,* 77-81.

Yue, L. J., & Qian, Y. L. (2020). Prediction of the Narrow-Thin Reservoir Based on Seismic Waveform Indication Inversion Technology. *Petroleum Geology & Oilfield Development in Daqing, 39,* 135-140.

Zhang, J. H., Liu, Z., Liu, B. Y., Zhu, B. H., & Feng, D. Y. (2012). Analysis and Identification of Reservoir Characteristics of Weak Reflectors under Strong Shielding Layer. *Special Oil and Gas Reservoirs, 19,* 23-26+135.

Zhang, Z. J. (2016). *The Research and Application of Seismic Prediction Methods for the Reservoir under Strong Shield*. China University of Petroleum (East China).

Zhang, Z. J., Zhang, J. H., Li, J., Zhang, H., Xia, H. M., & Lei, T. (2016). A Method for Stripping Coal Seam Strong Reflection and Low-Frequency Shadow Analysis. *Oil Geophysical Prospecting, 51,* 376-383.