Application of Seismic Motion Inversion in the Third Member of the Shahejie Formation in the Northeastern Kenli

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Abstract: The reservoirs in the third member of the Shahejie Formation in the northeastern Kenli are thin and laterally changing, so the traditional seismic attributes and inversion techniques have no ideal prediction effects for them, which fails to meet the needs of exploration evaluation. With the first application of the Seismic Motion Inversion technique in the work area, based on the seismic data, and guided by sedimentary laws and seismic geological features, this study carried out the HF inversion by making full use of the constrained seismic logging parameters, through the process that the waveform similarity and spatial distance constrained the preferable seismic trace to participate in the inversion operation. The inversion results show that the sandstone body structure and distribution pattern in the study area are clear. This improves the prediction ability of interwell thin reservoirs, and well describes the overlap boundary of thin-layer sandstone, having guiding significance for the next exploration and deployment work in this area.

1. Introduction

The northeastern Kenli is tectonically located in the slope belt of the eastern-Kenli buried-hill drape tectonic belt plunging to the Huanghekou Sag in the north. The strata of the third member of the Shahejie Formation overlap the Mesozoic Group, mainly forming stratigraphic overlap reservoirs [1, 2]. At present, multiple wells in the drilling-encountered third member of the Shahejie Formation have obtained commercial oil flow during drilling, and the oil and gas are locally enriched and high-producing, with the potential to form scaled reservoirs. In the actual exploration and development, it is found that the third member of the Shahejie Formation has typical characteristics of topographic-concealment stratigraphic overlap trap: In the sedimentary period of the third member of the Shahejie Formation, gullies developed, controlled by the paleo-geomorphology, the development was from the fan delta of the high in the eastern Kenli. The reservoir of the third member of the Shahejie Formation is relatively thin, approximately parallel to the top surface of the former Tertiary, the sandstone body and the unconformable surface are in the same strong reflection phase. The overlap-spot position interpretation is of great artificial randomness and non-uniqueness, and the reservoir identification is difficult. Besides, the seismic data shows a low frequency. The frequency for the target formation is about 35 Hz, and the effective frequency band ranges from 10Hz to 60Hz. The conventional seismic attributes and inversion techniques have low resolution and high
non-uniqueness, so they cannot be applied to the prediction of thin reservoirs\cite{3}. Under this context, it is urgent to find effective technical methods to further improve the accuracy of seismic prediction and realize the quantitative prediction for thin-layer sandstone bodies. In this paper, the Seismic Motion Inversion is applied and satisfactory geological effects are obtained.

2. Principle of Seismic Motion Inversion

Seismic Motion Inversion (SMI) is a new high-precision inversion method developed on the basis of traditional geostatistical inversion. It uses the SMCMC algorithm\cite{4, 6}, to seek for the common structural information contained in the logging curves corresponding to the similar waveform under the driving of seismic waveforms (Fig. 1), so as to perform the seismic prior finite sample simulation. The basic idea is: Based on the reference to the seismic waveform similarity and spatial distribution distance, the well with a high similarity and short spatial distance is preferred as the effective statistical sample to establish an initial model, and the unbiased optimal estimation is performed for the high frequency components to ensure the final inversed seismic waveform is consistent with the original seismic features, so that the inversion results spatially reflect the significance of seismic phase constraints, realizing the interwell reservoir prediction under the constraints of seismic waveforms, and making the longitudinal and lateral precision of the inversion are simultaneously improved, and it is more in line with the laws of geological deposition.

3. Technical Process of Seismic motion inversion

Based on the above inversion principle, preprocess the well logging curves first. Then, analyze the known well according to the characteristics of the seismic waveform. Prefer to the sample well having a high correlation with the waveform of the trace to be discriminated to establish an initial model, and calculate the longitudinal wave impedance of such model to establish prior information. Perform matched filtering on the initial model and the seismic wave impedance, and obtain the likelihood function by calculation\cite{7, 8}. Finally, combine the likelihood function and the prior probability under the Bayesian framework to obtain the posterior probability density distribution, perform sampling on the posterior probability density distribution and use it as the objective function. Constantly perturb the model parameters to maximize the posterior probability density value. The solution at this time is implemented as a feasible randomization. Take the average of multiple feasible implementations is taken as the expected value output. Combine the dominant frequency bands of different data bodies by using the combining function of the frequency domain data bodies, to improve the quality and effectiveness of the inversion.

Fig.1 Waveform Feature Analysis Diagram

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4. Application Examples

4.1. Main Technical Links

4.1.1 Reconstruction of Characteristic Curves

After the preprocessing of the logging curves in the study area, the petrophysical characteristics were studied to find the attribute parameters sensitive to the lithological changes of the target formation. The intersection analysis shows that the original wave impedance curve is weak to differentiate the reservoirs, and the impedance values of the sandstone and mudstone overlap with each other (Fig. 2 (a), so it is impossible to use the existing wave impedance curve for the inversion. However, the Gamma curve is good to differentiate sand-mudstone. Through the information fusion technology, the low-frequency information reflecting the background velocity of the formation in the acoustic wave was fused with the high-frequency information of the Gamma curve which is sensitive to lithology. The reconstructed acoustic curve amplified the velocity difference of the sand-mudstone, and after reconstruction, the wave impedance curve could identify the reservoirs very well, meeting the inversion requirements (Fig. 2 (b)).

![Fig. 2 Histogram of the Relationship between Wave Impedance and Lithology of the Third Member of the Shahejie Formation in the Northeastern Kenli](image)

4.1.2 Number of Effective Samples

The number of effective samples refer to the number of the wells whose near-well seismic trace waveforms are similar to the waveforms of the trace to be discriminated, and it is used to characterize the degree of influence of spatial variation of seismic waveforms on the reservoir. Since there are fewer wells in the drilling-encountered third member of the Shahejie Formation in the northeastern Kenli, it is difficult to determine the number of effective samples based on the number of samples and seismic correlation. We defined the number of the effective samples by sorting the samples according to the degree of similarity with the wells having the waveforms of trace to be discriminated, to participate in the calculation. From the inversion results (Fig. 3), when the number of samples was 4, the correlation was basically the largest, and the reservoir continuity was good and the vertical resolution was high at that time. After multiple inversions were carried out by adjusting the frequency parameters, it was found that when the number of samples was 4 and the inversion quality was always stable. Therefore, the number of effective samples for this inversion was determined as 4.
4. 1.3 Frequency Parameters

The frequency parameter controls the effective band range of the inversion result, and affects the resolution of the inversion. It consists of three parameters: low-, medium- and high-frequency groups of parameters, of which, the high-frequency parameters directly affect the inversion resolution. According to the analysis of seismic data, the main seismic frequency is about 35Hz, the effective bandwidth is about 10-60Hz, and the velocity of target formation is about 3850 m/s. Besides, according to the principle of seismic exploration, the resolution of seismic data is $\lambda/4$. To estimate the sandstone formation with the thickness of about 3m to be identified, and the seismic frequency band shall reach about 320Hz. Several skeleton profiles in the northeastern Kenli were selected to carry out the inversion test by adjusting the parameters multiple times. As shown in Fig.4, the higher the high-pass high-cut frequency is, the higher the vertical resolution will be, and the worse the lateral continuity will be. Therefore, the preferred high frequency parameters were: 45Hz for low-cut frequency; 60Hz for low-pass frequency; 350Hz for high-pass frequency; and 400Hz for high-cut frequency.
4.2 Analysis of Inversion Effects

4.2.1 Comparison of Inversion Profiles

The waveform inversion was carried out on the study area. In addition, the relative impedance inversion and the constrained sparse pulse inversion were used to compare the prediction of the target thin sandstone formation. The resolution of relative impedance inversion is too low to meet the requirements of thin reservoir prediction; due to the limitation of the seismic bandwidth, the sparse pulse inversion has a general low resolution and high non-uniqueness, so its ability to identify thin reservoirs is poor; the seismic motion inversion makes full use of the logging information in the vertical direction, and the resolution is much higher than that of seism, which can clearly reflect the details.

From the profile of connected wells, the low resistance represents mudstone and the high resistance represents sandstone. In the seismic motion inversion profile, the medium-high impedance development law is basically the same as that of the sandstone body (Fig. 5). The 5 to 10m reservoirs developed in KD893, KD894 Side and KD894 wells can be distinguished. The inversion results correspond to the wells’ impedance curves very well. The sandstone body distribution characteristics are clear in the horizontal direction, showing a high coincidence degree relative to the seismic waveform distribution trend and the actual drilling.
Fig. 5 Seismic Motion Inversion Diagram for Connected Wells in the Northeastern Kenli
From the effect of individual wells, the interpreted sandstone body’s thickness of the posterior Well KD88 is basically consistent with that of the sandstone in the seismic motion inversion (Fig.6). The sandstone structure with the thickness of above 7m is clear, and there is also response to the thin formation of about 3m. The inversion results well correspond to the integrated histogram of the stratum.

Fig. 6 Comparison of the Integrated Histogram and Waveform Indication Inversion Results of KD88 Well

4.2.2 Application Effect
The seismic motion inversion reflects the spatial variation of sedimentary environment and lithology combination. It utilizes the spatial variation of seismic waveforms and the bidirectional constraints of distance to perform the random simulation inversion, effectively reducing the randomness, based on the use of the high resolution of wells in the vertical direction, as well as the high resolution of seism in the horizontal direction. From the application in northeastern Kenli, the lateral variation of the thin reservoir of the third member of the Shahejie Formation is accurately reflected, the distribution pattern is clear, the inversion results are highly consistent with the actual drilling, and the internal structure and sedimentary evolution of the sandstone are reflected. Besides, the overlap spot of the overlap strata are clearly reflected, and the overlap boundary of the thin sandstone is accurately depicted (Fig.7) to show the distribution range of the reservoir as well.

This set of inversion data was used for the description of the overlap reservoirs of the third member of the Shahejie Formation in northeastern Kenli in the study area. A total of 5 km² favorable reservoirs were described, the predicted reserve was 6 million tons, which provides a good basis for the next exploration and deployment of this area and has certain guiding significance for reservoir prediction of other similar areas.
5. Conclusion

(1) The seismic motion inversion technology effectively combines seismic and geological information under the Bayesian framework to perform random simulation inversion by utilizing spatial variation of seismic waveforms and distance bidirectional constraints, which effectively reduces randomness and reflects the "phase control" idea in a better way compared to the traditional random simulation based on the variation function, improving the inversion precision, especially suitable for the fine prediction of thin reservoirs in mature exploration areas and development blocks.

(2) The seismic motion inversion improves the prediction ability of thin reservoirs in the third member of the Shahejie Formation in the Northeastern Kenli, and can identify thin sandstone body with an individual-layer thickness of 3m or more, and well describes the overlap boundary of thin sandstone formation, providing the guidance for the further reservoir prediction and exploration deployment work in the area.

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