A Comparative Study of Pre-Stack Fracture Prediction Methods for Coal Bed Methane

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Abstract. The No.8 coal seam in the Taiyuan Formation of the lower Permian with a burial depth greater than 2,000 m in the XX block of the eastern margin of the Ordos Basin has a confirmed reserve of over 100 billion cubic meters. It is currently in the pilot development stage using horizontal wells and large-scale hydraulic fracturing. Natural fractures are the foundation for the formation of complex fracture networks through hydraulic fracturing. Therefore, researching natural fractures is crucial for the transformation of horizontal wells and gas production efficiency. This article takes the No.8 coal seam in this area as an example, using high-quality five-dimensional seismic data with "two widths and one height," and calculating the anisotropy intensity by both ellipse fitting and azimuth statistics methods. Combined with analysis of structural stress fields, outcrop data, imaging logging, and array acoustic logging at different stages, the adaptability of these two methods to deep coal bed gas is analyzed based on the results, and the limitations of the ellipse fitting method are analyzed from a theoretical perspective. The research results show that the degree of fracture development in the southern part of this area is higher than that in the northern part, mainly consisting of two sets of fractures in different directions controlled by two periods of tectonic activity in this area. The Yan Mountain period formed fractures close to east-west and northwest directions, while the Xishan period formed fractures close to south-north and northeast directions. The above observations are consistent with the interpretation results of imaging logging, array acoustic logging, and reservoir fracture development reflected by fracturing wells, which verifies the rationality of the azimuth statistics method for fracture prediction. However, the traditional ellipse fitting

method cannot describe multiple sets of fractures due to its inherent limitations, making it unsuitable for this area. The fracture prediction results of the azimuth statistics method in this article play an important role in optimizing horizontal well fracturing technology and improving gas production efficiency, providing important references for the prediction of coal bed gas fractures in other blocks.

Keywords: No.8 coal seam · small-scale fracture prediction · five-dimensional seismic data · anisotropy

1 Introduction

The XX block on the eastern edge of the Ordos Basin has confirmed reserves of over 100 billion cubic meters of coalbed methane in the No. 8 coal seam with a burial depth of over 2,000 m. It has entered the stage of pilot development using horizontal wells and large-scale volume fracturing, and natural fractures form the basis for the formation of complex fracture networks through hydraulic fracturing. Therefore, the study of natural fractures is crucial for the transformation of horizontal wells and gas production effects.

Currently, there are three main types of seismic data prediction and identification techniques for fractures: post-stack 3D seismic attribute prediction technology, multi-wave and multi-component prediction technology, and longitudinal wave azimuthal anisotropy prediction technology [1]. Generally speaking, post-stack 3D seismic attributes can only predict fractures larger than 1/4 wavelength; multi-wave and multi-component prediction technology is greatly limited due to high acquisition and processing costs, as well as difficulties in pure transverse wave exploration, while the prediction of fractures based on longitudinal wave data collected using "two-width and one-height" acquisition has unique advantages, especially five-dimensional seismic data containing more information about reservoir fractures and other anisotropies [2–4], providing data support for anisotropic fine characterization of fractures.

Extracting fracture information based on five-dimensional seismic data has received increasing attention [5–7] and has been widely used in fracture prediction in sandstones, shales, carbonates, and other formations [4, 8–10]. However, predicting small-scale fractures before stacking in deep coalbed methane fields is still being explored for the first time. In coal seams, the presence of coalbed methane accumulation and fractures not only reduces the volumetric density of coal but also significantly affects elastic mechanical parameters such as elastic modulus, Poisson's ratio, elastic wave velocity, spectral characteristics, attenuation coefficients, and quality factors [11, 12]. This provides a theoretical basis for studying coalbed methane and coal seam fracture characteristics using seismic data that contain rich geological information.

Previously, fracture prediction was carried out based on post-stack 3D seismic data in this area, but the accuracy rate of fracture prediction was less than 40%, which did not achieve the desired results. Therefore, an attempt was made to use pre-stack data from the OVT domain to predict fractures. The main method for detecting fractures based on azimuthal anisotropy information in pre-stack data is based on the prediction of anisotropic intensity using elliptical fitting. Hence, this paper first applied the elliptical fitting method to predict the anisotropic intensity of deep coalbed methane reservoirs

in the Daji block on the eastern edge of the Ordos Basin. The results were analyzed in conjunction with drilling array acoustic logging, pointing out the problems of the elliptical fitting method in this area, and analyzing the limitations of the elliptical fitting method in principle. At the same time, to overcome the flaws of the elliptical fitting method, this study applied the azimuthal statistical method for predicting anisotropic intensity in this area for the first time and finely characterized the degree and direction of fracture development in the No. 8 coal seam in combination with information from various periods of paleo-structural stress fields, field outcrops, imaging logging, and array acoustic logging. The predicted fracture results were consistent with those reflected in imaging logging, array acoustic logging, and actual fractured wells, verifying the rationality of the method and playing an important role in optimizing the horizontal well fracturing process and improving gas production efficiency in coalbed.

## 2 Prediction Principle of Pre-Stack Vertical-Wave Anisotropy Fracture

Using longitudinal wave seismic for crack detection is an important work in the description of fracture reservoirs. Scholars both domestically and internationally have conducted a lot of research on this. Among them, the most researched method is using changes in amplitude, velocity, and time difference with respect to the observation azimuth to identify fractures. Sena [13] pointed out that in an anisotropic medium, the longitudinal wave speed undergoes periodic changes with the variation of the azimuth, and the change relationship has elliptical characteristics. Winkler [14] derived the conclusion that the longitudinal wave time differences undergo periodic changes with the variation of the azimuth in crack media through laboratory observations and deductions. Stephen A. Hall and J-Michael Kendall [15] described cracks using longitudinal wave amplitude changes with respect to the azimuth and shot-receiver distance.

(1) **Anisotropy strength based on ellipse fitting method**

Haoshaoling et al. [16], based on the anisotropic characteristics of fractures to longitudinal waves, conducted simulation experiments (Fig. 1). For OVT gather, it was found that changes in amplitude, travel time, or velocity with respect to the azimuth can be approximated by an elliptic equation:

$$F(\phi) = A + B\cos 2\phi \tag{1}$$

where phi is the angle between the observation azimuth and the fracture. When phi = 0°, F(0°) = A+B represents the maximum response value, which is the direction of the fracture. When phi = 90°, F(90°) = A−B represents the minimum response value, which is the direction perpendicular to the fracture. Anisotropy strength prediction based on ellipse fitting requires stacking of local offset and azimuth of the gather, extracting the amplitude (i.e. AVAZ) or other information (such as frequency information, FVAZ) from each stacked local offset-azimuth gather, fitting an ellipse, and calculating the major and minor axes to determine the anisotropy strength based on formula 1.
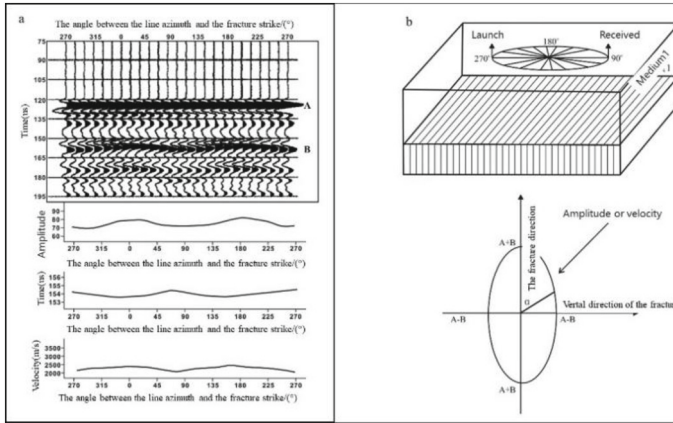
Fig. 1. Sketch map of P wave azimuthal anisotropy vertical to fracture media (a), Physical model trial of azimuth anisotropy (b), Ellipse fitting schematic map

(2) **Anisotropy strength based on statistical method**

Statistical method for anisotropy strength is also based on the principle of AVAZ, but unlike ellipse fitting, there is no stacking of local offset-azimuth, instead directly calculating the variance of amplitude or two-way travel time in the OVT gather. The variance is a scalar, and the size of the variance indicates the strength of the anisotropy at that point [17].

$$\beta \approx \frac{\pi}{2N} \sum_i \frac{\left| R_i - R_i' \right|}{R_i'} \tag{2}$$

$$R_i' = \frac{1}{M} \sum_{j=1}^{M} R_{i,j} \tag{3}$$

Formula (2) is the discrete formula for calculating variance, where beta represents the variance, N represents the number of discrete azimuth sample points, Ri represents the amplitude or two-way travel time of an azimuth offset point in the gather, R'i represents the average amplitude or two-way travel time, and M represents the number of shot-receiver distances that are discretized. M and N are determined by interpolation in the shot-receiver distance-azimuth domain.

3 Ellipse Fitting Method, Azimuthal Statistical Method for Anisotropy Strength Prediction and Problem Analysis

3.1 Seismic Geology of Study Area

The XX block is located at the southern end of the Jinxi flexure belt on the eastern margin of the Ordos Basin and the southeastern part of the Yishan slope. It is located in the transition zone between mountains and plains, where thwhere phi is the angle

betweene mountainous terrain has been eroded by weathering and runoff, and the surface conditions are complex with large changes in elevation ranging from a minimum of 500 m to a maximum of 1500 m. The surface is covered with Quaternary loess, and sandstone outcrops in the river valley areas. The surface conditions are complex with significant vertical and horizontal variations in lithology. The block is clearly divided into different tectonic zones from east to west, including the eastern slope zone, Taoyuan anticline zone, central steep slope zone, and western gentle slope zone. The study area is mainly located in the western gentle slope zone where the structure is relatively flat, faults are not developed, and dip angles are generally less than 2°. The main target coal seam for exploration and development is the No.8 coal seam of the Taiyuan Formation, which is buried at depths ranging from 2000 to 2400 m (Fig. 2).
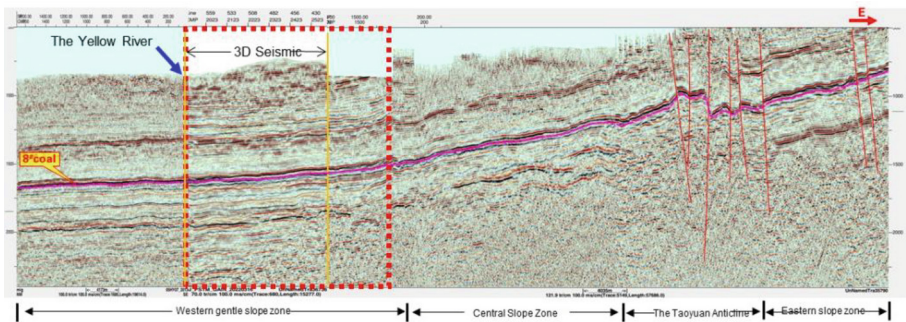

Fig. 2. Location east-west seismic profile of the study area

The No.8 coal seam is thick, with a thickness of 3–12 m and an average of about 6 m. It has a wide distribution range and 1–2 layers of mudstone intercalations in the middle of the coal seam. The roof is a thick layer of limestone of the Taiyuan Formation, and the floor is a thick layer of mudstone. Due to the small impedance difference between sand and mudstones, internal reflection layers are relatively rare. The large impedance difference between coal seams and roof/floor formations can form good coal seam reflection waves. In summary, the seismic geology conditions of the surface and shallow layers in the study area are poor, while those of the deep layers are good.

3.2 Analysis of OVT Gather Data in the Study Area

In 2021, the "two-wide-one-high" seismic data acquisition was carried out in the study area, with a sampling interval of 20 m × 40 m, coverage of 210 times, scanning frequency of 4–80 Hz, and an aspect ratio of 0.7. The seismic data has been greatly improved in terms of imaging, signal-to-noise ratio, frequency bandwidth, etc. compared to 2D data, and provides OVT gathers as a basis for pre-stack fracture prediction. By dividing the seismic data of the "two-wide-one-high" acquisition with specific data tolerance, data that contains specific offset and azimuthal information can be obtained, which is the OVT [3, 10]. The processing of OVT gather data in this area includes OVT data extraction, OVT data regularization, OVT migration, and OVT gather processing,

resulting in flattened and significantly improved signal-to-noise ratio gather data (Fig. 3). On the common azimuth gather display profile, the No.8 coal seam in the OVT gather shows an increase and then decrease in amplitude with increasing offset distance. On the common offset gather display profile, the amplitude of the same phase axis of the gather changes with the variation of the azimuth (Fig. 4). This indicates that the OVT gather data in this area has directional anisotropy characteristics and has a data basis for conducting directional anisotropic fracture detection based on gather data.
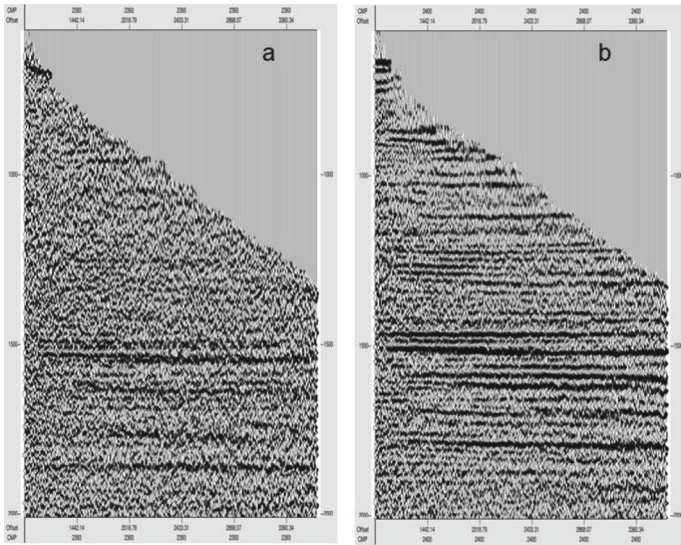

Fig. 3. OVT track set comparison diagram (a), Original OVT track set (b), Optimized OVT track set

3.3 Anisotropy Strength Prediction and Analysis

The ellipse-fitting method was used in Geoeast-ET software for azimuthal anisotropy strength prediction. The flow of the ellipse-fitting method for anisotropy strength prediction is as follows: ①Define the analysis template based on the fracture direction indicated by the imaging logging or the fault trend in the study area; ② Extract corresponding seismic attributes from seismic data formed by 15 different offset distances combination, perform ellipse fitting, optimize the offset distance according to the dispersion degree of ellipse fitting; ③Extract amplitude, frequency, travel time, and other attributes of anisotropic data volume along the target layer, preferentially select sensitive attributes according to the dispersion degree of ellipse fitting, and evaluate the orientation, intensity, and reliability of fractures. Firstly, the fracture direction is defined based on the imaging logging of wells DD3–4 to define the analysis template. Then, through ellipse fitting, the dispersion degree of ellipse fitting is compared, and the 15 built-in shot-gather distance combinations of the software are optimized. According to the dispersion degree

of the ellipse, the effective shot-gather distance range in this area is 3301 m. Based on the optimized shot-gather distance, sensitive attributes are preferred, mainly by comparing the anisotropy strength and dispersion degree of ellipses displayed by different attributes with respect to azimuth. The maximum amplitude attribute of this area shows strong anisotropy strength and uniform dispersion of the ellipse, so it is chosen as the sensitive attribute for azimuthal anisotropy to characterize the degree of fracture development in this area. Figure 5(a) shows the results of the ellipse-fitting method in this area. Figure 5(b) shows the results of the azimuthal statistical method in the study area.
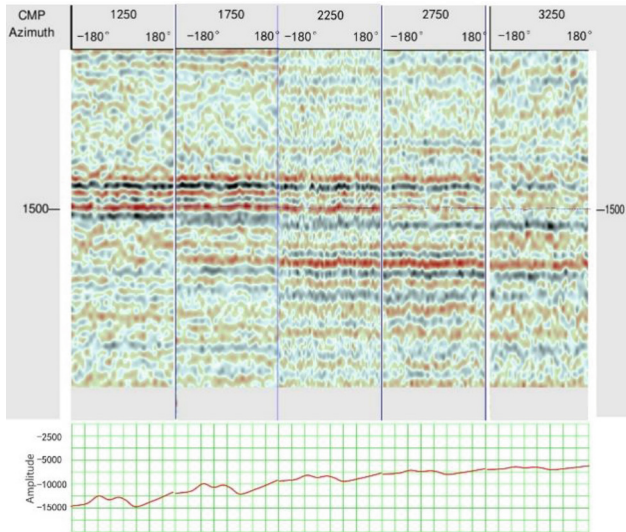

Fig. 4. Common offset distance gather profile

The basic idea of the azimuthal statistical method for anisotropy strength prediction is to compare the differences in data attributes between different directions at the same shot-gather distance. Therefore, the key step of the azimuthal statistical method for anisotropy strength prediction is the explanatory processing of shot-gather distance-azimuth angle rectangular regularization based on OVT domain gather processing. After the rectangular data is regularized, the seismic traces with the same sampling number are calculated from seismic traces of the same azimuth with different shot-gather distances. The slice amplitude consistency of the gather set is better than that before regularization, and the signal-to-noise ratio is improved to some extent (Fig. 6).

The overall trend of anisotropy strength predicted by both methods has a high similarity, showing that fractures develop more in the southern part of the study area than in the northern part, and the fracture direction is mainly NW, EW, and NE, with a small amount of SN, which is consistent with the stress background of the Yanshan period and Xishan period in the region [18]. In addition, The only imaging logging data in this area shows that the fracture direction is NE, which is consistent with the predicted fracture direction.
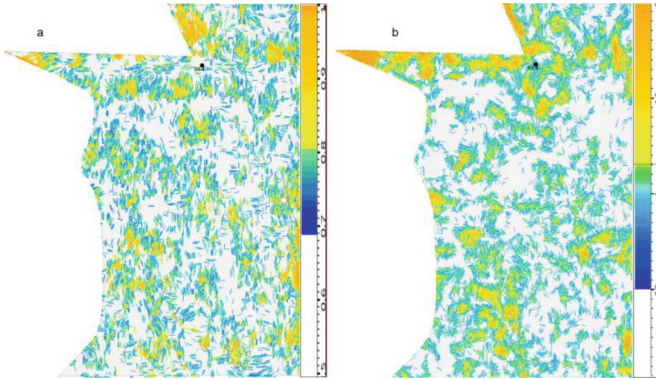
Fig. 5. Anisotropy strength distribution maps (a), Ellipse fitting method (b), Azimuthal statistical method
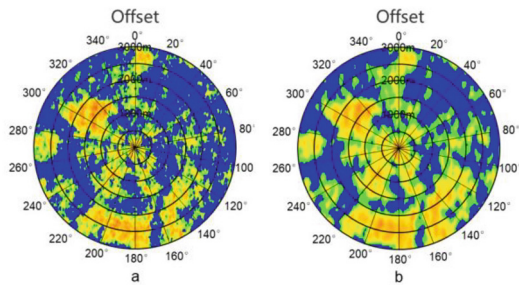

Fig. 6. Full azimuth gather slice amplitude (a), Original OVT gather (b), Gather after rectangular regularization

However, there are differences in the details of the anisotropy strength predicted by the two methods from the local plane distribution (Fig. 7). There is a large amount of array acoustic logging data in this area. Array acoustic logging measures anisotropy by characterizing the difference between fast and slow shear waves within the drilled wellbore. In contrast, three-dimensional seismic surveys use seismic sources outside the drilled wellbore to propagate vibrations longitudinally, which exhibit directional changes in seismic wave propagation to characterize anisotropy. Essentially, the anisotropy detected by the 3D seismic data and the logging anisotropy both reflect the heterogeneity of the formation. Therefore, the anisotropy obtained by horizontal wave logging can be used to validate the anisotropy predicted by the ellipse fitting method and the azimuthal statistical method.

From the comparative results, the trend of anisotropy strength predicted by the azimuthal statistical method is consistent with that of logging anisotropy. The reason for this is that the ellipse fitting method produces different results depending on the chosen stacking scheme during offset distance stacking (Fig. 8). This local offset distance stacking algorithm may be the cause of errors in prediction results. On the other hand, the anisotropy strength based on azimuthal statistics directly calculates attributes such
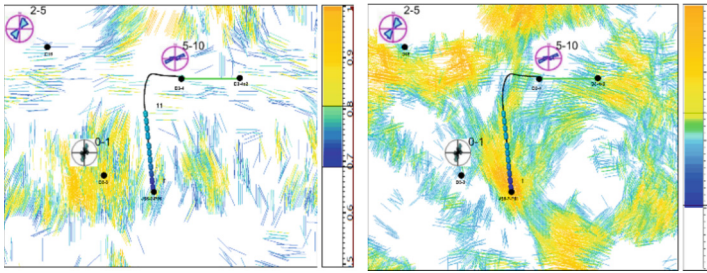
Fig. 7. Local anisotropy strength distribution maps (a), Ellipse fitting method (b), Azimuthal statistical method

as amplitude and travel time variance in OVT gathers, without the need for stacking of offset distance and azimuth angle.
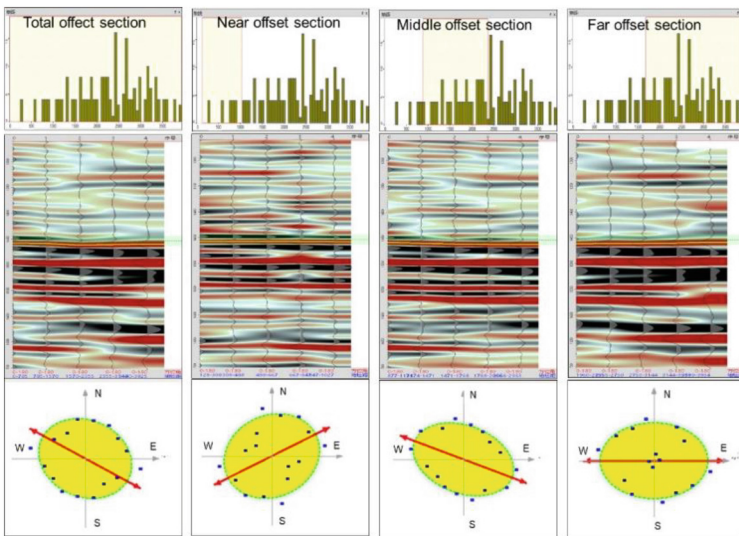

Fig. 8. The map of different offset distance imaging and ellipse fitting results

4 Instance

In terms of the interaction between hydraulic fractures and natural fractures, scholars at home and abroad have conducted research from various aspects, pointing out that natural fractures in reservoir rock are the basis for hydraulic fracturing to form complex fracture networks [19–22]. The intensity of fracture development directly affects the extension of the hydraulic fracture, and can directly reflect the suspected risks of hydraulic fracturing construction. Therefore, the prediction of natural fractures has been widely used in the process of selecting horizontal well fracturing intervals in deep coal seam gas, including optimizing fracturing processes and identifying risks of casing transformation.

In the application of fracturing process optimization and evaluation, the D13-6 platform in the study area is taken as an example. The D13-6 well platform is located on a northwestern-southeastern trending local positive structural background, with overall favorable structural conditions. All three horizontal wells are up-dip wells drilled to the south, with wells 01 and 03 located on the minor deformation flank, exhibiting negative curvature deformation; well 02 is located at the high point of the minor deformation, exhibiting maximum positive curvature deformation. The fracture prediction results show that fractures in this well platform are well developed, and the ant body enhancement processing shows clear characteristics of the fracture zone, which extends east-west near point B of the horizontal well in the southern part of the well platform. Based on the degree of deformation and curvature changes of the D13-6 well platform, especially the development of natural fractures in the horizontal section, a differentiated fracturing interval selection scheme was established according to the geological conditions of the reservoir. In order to improve the overall utilization of resources and initial production, the number of cluster stages was optimized based on the abundance of coal seam resources. The length of each fracturing stage was determined based on the degree of fracture development, with longer lengths for more developed fractures and shorter lengths for less developed fractures. The number of perforation clusters was optimized based on the form of fracture development, with fewer clusters for intersecting fractures and more clusters for oblique fractures (Fig. 9).
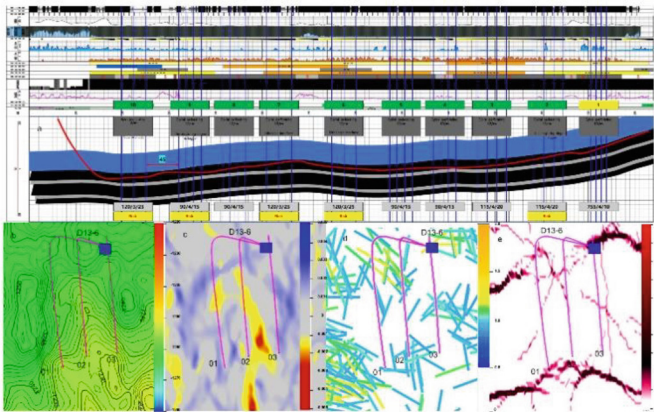
Fig. 9. Comprehensive analysis of fracturing stage selection for well DD13-6 plat01 (a), Selection map of fracturing stages (b), Structural map (c), Maximum curvature map (d), Fracture prediction map (e), Ant body map

From the effectiveness of the fracturing implementation and production, it can be seen that fractures are well-developed in the region, and large-scale fracturing based on reservoir conditions has achieved volume fracture network transformation, with good current production results, reaching 231,000 m^3 per day for all three wells, and maintaining high pressure retention levels. The results of fracture prediction effectively guided the evaluation of differentiated fracturing interval selection for horizontal wells and on-site fracturing construction.

In the application of identifying casing deformation risks, preliminary investigations indicate that casing deformation in horizontal wells during large-scale fracturing is generally caused by shear slip at fracture locations, which mostly occur at places where faults and natural fractures are developed. Therefore, it is urgent to focus on the possibility of casing deformation occurring in well sections due to fracture development and include this consideration in the fracturing design scheme during the process of selecting fracturing intervals and designing fracturing engineering. Taking the D14-5 platform as an example, perforation encountered resistance at 3449 m of well D14-5-02. And perforation encountered resistance at 3324.28 m of well D14-5-01. In both wells, the construction obstruction occurred in a zone with developed natural fractures, and ant body enhancement processing showed clear characteristics of the fracture zone (Fig. 10). It is speculated that the injection of a large amount of liquid during fracturing reduced the normal stress within the fracture, causing the fracture to slip and resulting in casing deformation. Therefore, during the process of selecting fracturing intervals, it is necessary to clarify the points of attention and risk points for fracturing based on the spatial relationship between the horizontal wellbore and the reservoir and the fracture prediction results from ant body enhancement processing, in order to guide fracturing engineering design and on-site construction.
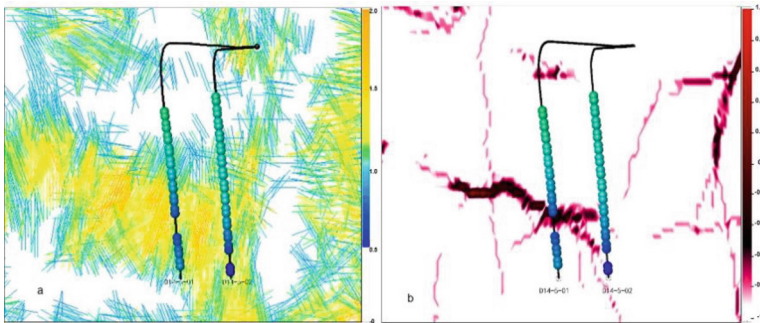
Fig. 10. Fracture prediction map of DD14-5 well platform (a), Anisotropy strength (b), Ant body of anisotropy strength

5   Conclusion and Understanding

(1) Through the study of small-scale fracture prediction in deep coal seam gas reservoirs in the Daji block, it was clarified that post-stack seismic fracture prediction technology has strong multi-solution ambiguity and identifying small-scale fractures in deep coal seam gas reservoirs is more difficult. However, the common image-point traces obtained through OVT-domain migration processing based on "two widths and one height" seismic data retain directional information, providing a reliable data foundation for utilizing directional anisotropy technology to finely characterize coal reservoir fractures.

(2) The ellipse fitting method has always been a classic algorithm for describing fracture orientation and density. This method is simple and resistant to noise for data with low coverage and low signal-to-noise ratios, and can effectively describe the development of single-directional fractures. In this area, due to multiple periods of structural stress transformation, two sets of fractures with different directions are developed, making the applicability of the orientation statistical method better in this area.

(3) Two sets of fractures were developed in the study area, matching the two periods of structural stress received in this area. The Yanshan period structural stress field formed fractures near the EW and NW directions, while the Xishan period structural stress field formed fractures near the SN and NE directions. The predicted degree of fracture development is consistent with the reservoir fracture development reflected by imaging logging, array acoustic logging, and fracturing wells, which has played an important role in optimizing the horizontal well fracturing process and improving gas production effects in deep coal seam gas reservoirs in this area. The prediction method can provide reference for fracture prediction in other blocks of deep coal seam gas reservoirs.

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