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Case Report

Pre-stack Anisotropy Fractures Detection Based on OVT Domain Gather Data and Its Application in Ultra-deep Burial Carbonate Rocks

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Abstract: There are abundant fracture cave reservoirs wrapped in Ordovician tight limestone in the Tarim Basin, with an average buried depth of 7000m. The connectivity analysis of fracture-porous systems and hydrocarbon-bearing analysis has essential roles in the deployment of high-efficiency wells of the Ordovician carbonate reservoirs in the Tazhong and Tabei areas of Tarim Basin, as they are the major targets for increasing production. However, in the previous researches, the pre-stack fractures' prediction and the oil/gas detection results using conventional processing data were lack of accuracy, which failed to complete the need of high-precision exploration and development. Firstly, the paper systematically analyzes the characteristics of azimuthal anisotropy analysis using conventional processing seismic data. Then it explains the process of selecting data, which is capable to meticulous reflect anisotropy characteristics of the formation and contains uniformed coverage to improve convergent results of elliptical fitting. Finally, the paper focuses on the three steps of operating azimuthal anisotropic pre-stack fracture detection using common reflection angle gather and receiving a reliable result. Practice demonstrates that using common reflection angle gathers during research of fractures in carbonate rock has a distinctive effect, which can provide a decisive basis for the layout of high-efficiency well groups in the development block.

Keywords: Azimuthal Anisotropy, Pre-stack Fracture Detection, OVT Domain Gather, Reliable Analysis, Carbonate Reservoirs

1. Introduction

The Ordovician carbonate reservoirs are developed in Tabei area of Tarim Basin and are deep buried (about 7000 m) with strong inhomogeneity [1, 2]. It can be divided into three types: porous, fracture and fracture-porous reservoirs. The matrix pores are not developed in the Ordovician carbonate reservoirs, while micro-fractures and pores are visible (Figure 1). With further exploration and development, the large-scaled fractured-vuggy reservoirs with fractures have become to the major research targets. However, the unclear connectivity of the fracture-porous system restricts the deployment of high-efficiency well groups. Since 1990s, there is an upsurge of using P-wave anisotropy to detect fractures, which targets on diversities of travel time and amplitude generated by P-waves in various directions [3]. The experimental results of a rock physics model demonstrate that the propagation velocity of seismic P-wave is larger along the direction which parallels to fracture compared to perpendicular direction, and the difference reaches to 18%-19% [4]. Based on Thomsen, seismic attributes such as azimuth amplitude, azimuth velocity, azimuth AVO/FVO gradient and azimuth frequency are sensitive to fractures. He also advised that the density of fractures can be calibrated. Although the theory of fracture prediction is relatively mature, there are still many problems in practical applications [5].

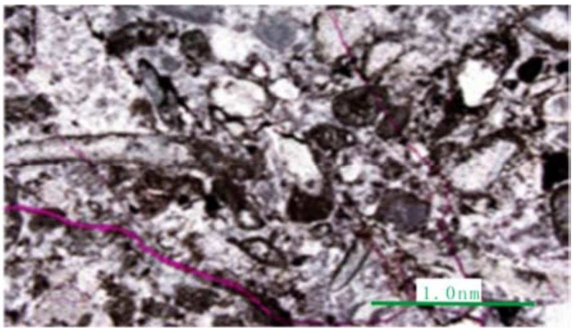


Figure 1. *Core characteristics of TO2y from a well belongs to the Halahatang oil field of Tabei area.*

Previous azimuthal anisotropy pre-stack fracture detection is producted on sub-azimuth data [7, 8]. Original data is divided by azimuth and collected as a sector in a certain azimuth range, then it is extracted separately to process offset migration. The azimuth information in a sector is ultimately stacked as one value. For predicting fractures, attribute values of each point in every trace are extracted and corresponded to an azimuth coordinate system (polar coordinate system), then operated ellipse fitting [9-12]. Because the lack of azimuth and offset information, prediction results are inaccurate and hard to satisfy the development and production of carbonate fracture-porous reservoirs in study area. However, Offset vector tile (OVT) domain gathers contains not only spatial position, amplitude and frequency, but also consists of azimuth information. Because each point in the data has its own offset and azimuth, the OVT coil gather is more conducive for azimuthal-anisotropy fracture detection. Furthermore, based on the optimized data, the fracture detection method is modified to be more efficient during the application in the oilfield.

This paper discusses the research and application of fracture detection using common reflection angle gather in order to solve the problems in high-precision exploration and development.

2. Data Optimization and Fracture Detection

2.1. Data Selection

The pre-stack azimuthal anisotropic fracture detection has been practiced in Halahatang for many years, and is critical during the connectivity analysis of the fracture-porous system. However, the method requires a high-quality azimuthal data with uniform coverage.

Based on an example of high-density full azimuth seismic panel attribute map (Figure 2a), clearly each azimuth has various folds and incident angle (offset). The conventional method divides the common mid-point (CMP) gather into several azimuthal sectors, and processes migrating and stacking separately for each sector, followed by ellipse fitting to identify fractures.

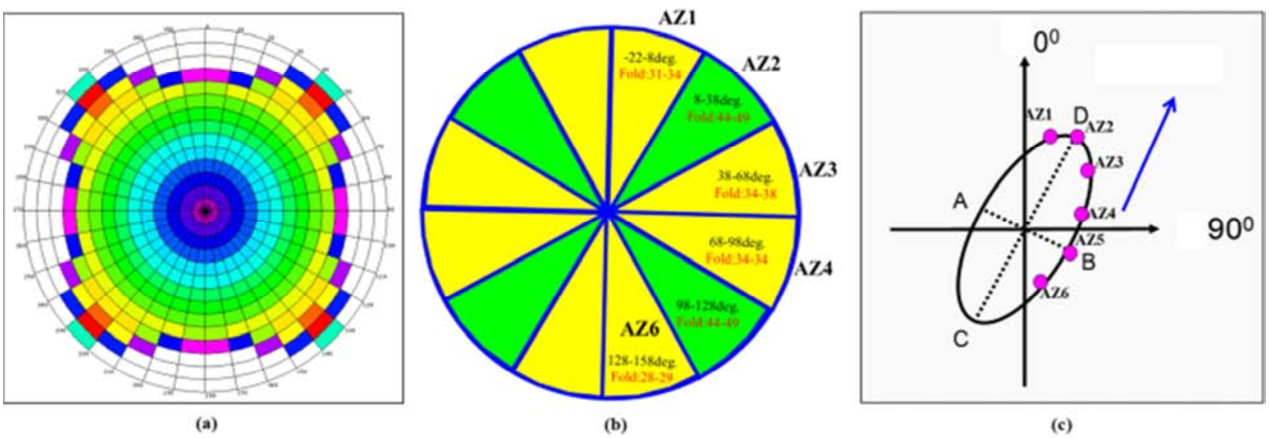


Figure 2. *Seismic coverage plot, Azimuth division of conventional process and An sample of ellipse prediction. (a) Different colors for different folds, (b) degree is written in black color and the folds is written in red color; green areas are advanced sectors, (c) The blue arrow indicates a crack trend.*

There are five major shortages in the sub-azimuth process. First, the folds are not equal for each azimuth sector (Figure 2b). The difference is caused by seismic acquisition when variable data is received in various azimuth sectors. Second, full offset data is severely influenced by the near and far offset data, and lead to azimuth data with false anisotropic characteristics of formations. The near offset data has an extremely small incident angle for deep burial formation, which lead to strong energy and lack of anisotropy features. While remote offset data contains few coverage, which failed to enhance the quality. Third, there is a contradiction between the division of azimuthal sectors and principles of ellipse prediction (Figure 2c). With fewer azimuth divisions, the elliptic fitting has multi-solutions. However, the more azimuth divisions the data has, the less coverage it contains and the lower signal-to-noise ratio and reliability it achieves. Fourth, the azimuth division is an irreversible process that has a direct effect on the final result of fracture detection. Last but not the least, during the stacking of offset and azimuth value, enormous information would be lost, which has a negative impact during the fracture identify.

Therefore, it is important to optimize the input data using an appropriate method. With the improvement of advanced processing technology, there are several ways to process the common reflection angle gather which includes OVT domain process. Duan et al. (2013) proposed OVT coil gathers is consisted of seismic traces with roughly same offset and azimuth. It is a single coverage data body covering the entire work area, which has more details and can reflect more accurate for anisotropy features [13]. The advantage of OVT domain gathers is it abandons the idea of azimuth division. Through modifying offset and bin surface, original has been optimized to reduce negative influence from various folds and improve the contrast between azimuth division and ellipse fitting. In addition, seismic data with strong energy and weak anisotropy are eliminated to highlight true azimuthal anisotropy characteristics of formations.

2.2. Fracture Detection Theory

With better original data, this paper focuses on satisfying the high requirements to seismic data by three steps. Firstly, optimizing the incident angle of ES360 output common reflection corner gathers (Figure 3). Selecting data that consists of uniformed folds and relatively balanced energy to ensure the data participating in the ellipse fitting is converged [11]. Secondly, improve the stability of the ellipse fitting through credibility analysis and quality control. By calibrating the eccentricity of the fitted ellipse, the credibility increases with larger eccentricity (0-1) and fewer solutions. Thirdly, interactively analyzing seismic data with the drilling data, ensuring the long axis of the fitted ellipse (predicting the crack by the amplitude information) is consistent with the fracture orientation of FMI image logging. These procedures are designed to improving the accuracy of fracture detection and providing reliable evidence to fracture cavity connectivity analysis.

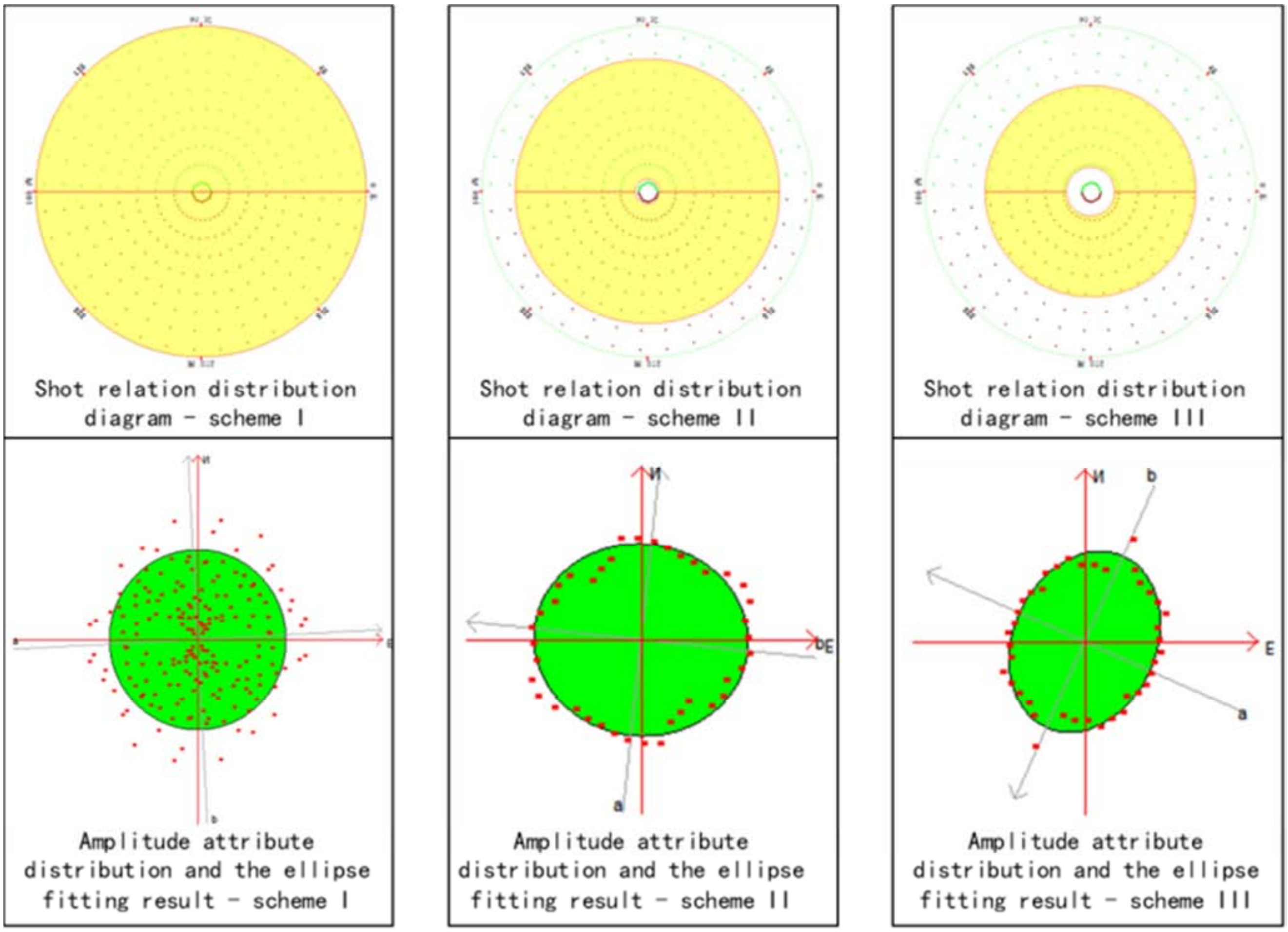


Figure 3. *Based on the common reflection angle gather offset optimization contrast chart.*

The application demonstrates that there are two major advantages of fracture prediction using common reflection angle gather data. On one hand, by using common reflection angle gather data, effective data can be extracted by methods such as optimizing offset and surface stacking. Without the concept of azimuth division, it eliminates the influence from various folds and the contradiction between azimuth division and ellipse prediction. Furthermore, data with small incident angle and weak anisotropy is discarded, which highlights true azimuth anisotropy characteristics of the stratum. On the other hand, interactive analysis and quality control on the interpretation platform benefited the result of drilling comparative analysis and fracture prediction. Take H601-4 well in Halahatang Oilfield as an example, the prediction result after optimizing data, conducting reliable analysis and quality control is more accurate and precise than the previous one which uses full incident angle gather as original data. The interference of NS and WE–trending is effectively eliminated, and the prediction direction of H601-4 well is correlate with drilling (Figure 4). According to the practice, this method can effectively improve the accuracy of fracture detection.

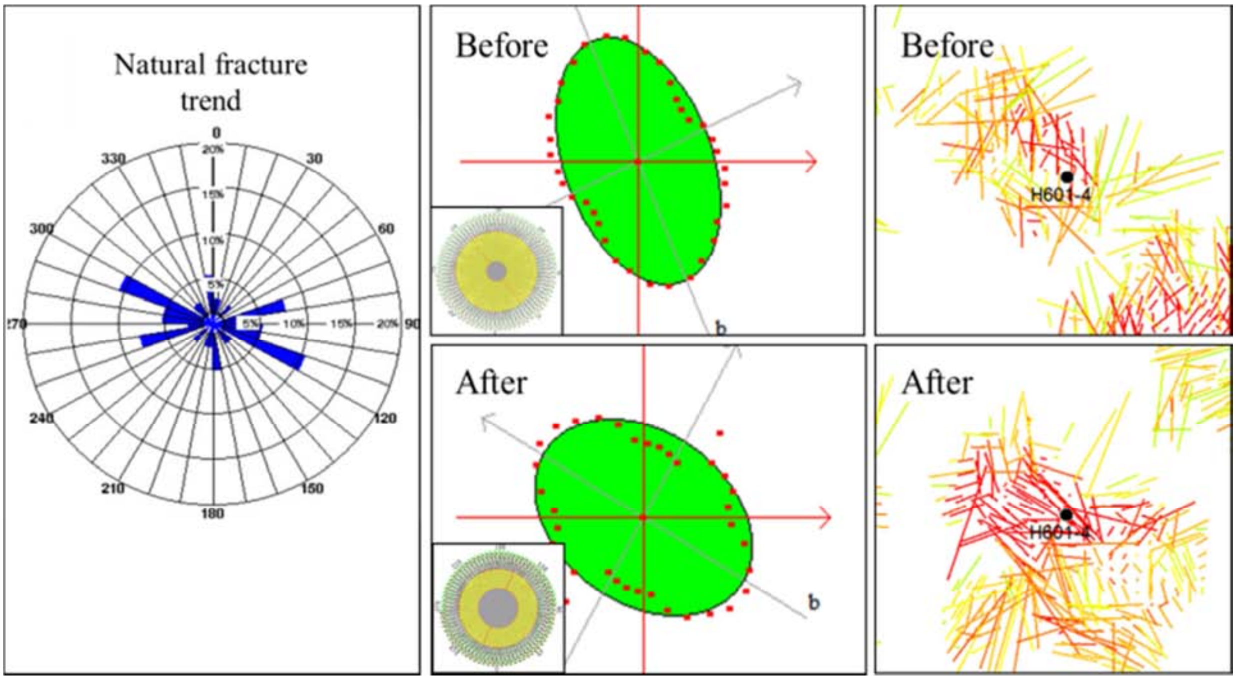


Figure 4. Comparison chart of H601-4 well fracture detection results before and after optimization.

2.3. Auto-Optimize Method of Fracture Detection

After the initial optimization of offset and azimuth staking, the Radial-Basis Function (RBF) neural network algorithm is used for classification, non-linear control and pattern recognition.

2.3.1. Theory

Powell proposed the Radial-Basis Function (RBF) method in the middle of 1980s, which has multiple variables [14, 15]. The basic idea of the RBF neural network is to use the radial basis function as the "base" of a hidden unit (the number of hidden elements is determined by the problem) or the input layer. The hidden layer uses non-negative non-linear function which is radial-symmetric and attenuates to the center point as the transform function. It transfers low dimension input data into high dimensional space and makes linear indivisible problems in low dimensional space linearly separable in a high dimensional space. The last layer is the output layer, where responses are made to the input layer information. According to the structure of the algorithm, the RBF neural network belongs to multi-layer forward neural network. It not only has relatively simple structure and training process, but also has a fast speed of convergence and can approximate to any nonlinear function. Therefore, the RBF neural network algorithm is widely used in various industries.

There are different forms of radial basis functions [16], such as Gaussian, Multi-Quadric, Inverse Multi-Quadric, and Cauchy functions. The most common used is the Gaussian function. The formula is:

$$h(X) = exp\left(\frac{\|X-C\|^2}{2\sigma^2}\right) \quad (1)$$

The variable C is the central vector of the Gaussian function, and the radial basis functions in the hidden nodes all produce the same output. The closer the input X is to the center C of the RBF, the greater the response of the hidden node. Therefore, the width of the basis function curve can be adjusted by adjusting the value of the radius σ.

2.3.2. Process

The basic flow of predictive parameter template auto-optimize method contains 5 stages. The first. Optimizing basic data and establishing primary parameter frame of azimuth stacking number and offset based on seismic acquisition parameter such as aspect ratio and folds (Figure 5a). The second. Identifying iteration times, and performing second optimization and classification of data that generated from primary parameter frame (Figure 5b). The third. Using optimized data from the second stage and FMI log of target layer from one well to perform training and non-linear control. Then automatically selecting the most reliable parameter of ellipse fitting as parameter template (Figure 5b) and establishes parameter template for all wells in test area that have FMI log. The fourth. Applying interpretation of FMI logging data and training results from all wells in the test area to perform pattern recognition and cluster analysis. Dividing test area into different sectors based on cluster analyse results. The fifth. extracting the optimal parameter results (the number of results is related to the given number of iterations) of fracture prediction from divided sectors as the comprehensive prediction parameter for the whole test area.

The automatic optimization module under fracture prediction template is divided into six functional modules: (a) primarily optimize parameter frame of azimuth stacking number and offset; (b) set number of iterations; (c) input interpretation of FMI log; (d) storage of the optimal module; (e) SNR analyse of elliptical fitting result that calculates from total number of iterative modules. Vertical axis is azimuth angle while horizontal axis is confidence degree; (f) monitor sample distribution in polar coordinate system during ellipse fitting and ellipse fitting result.

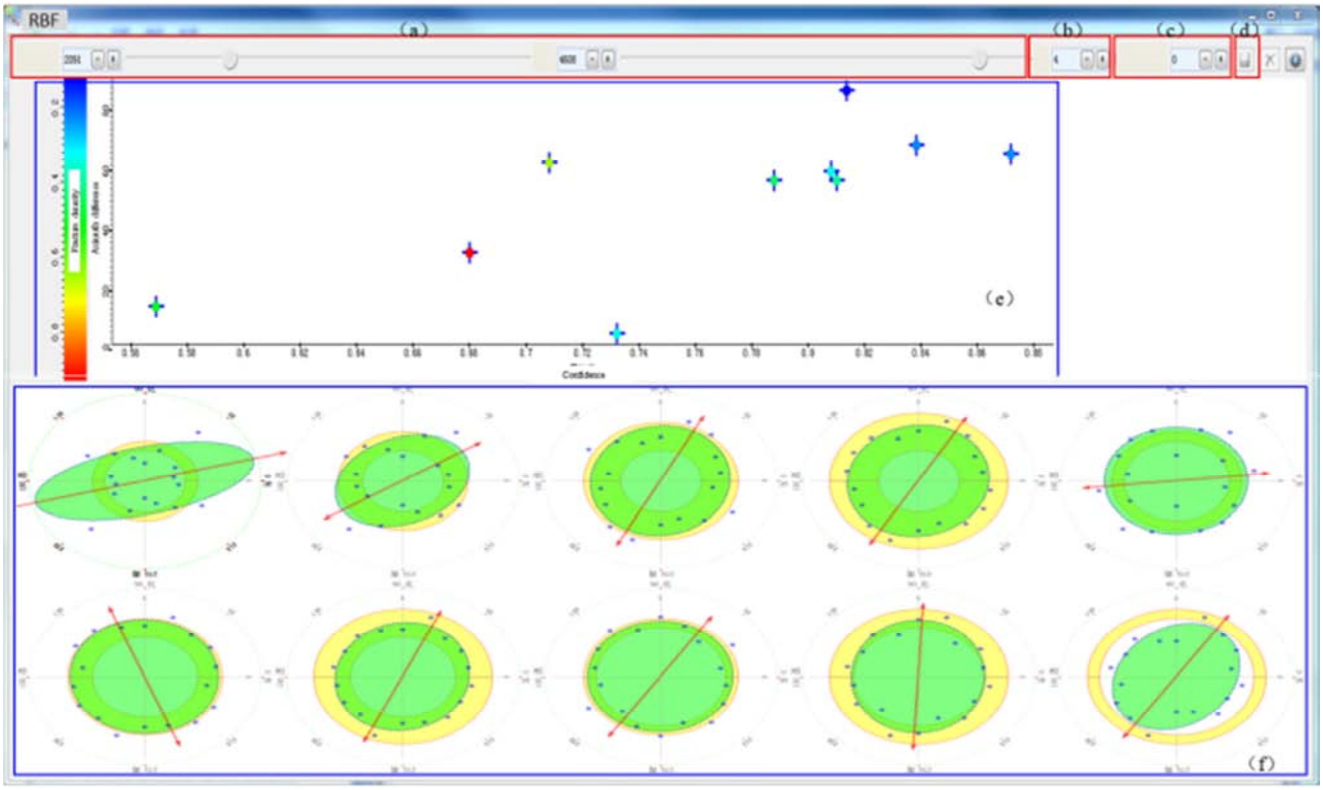


Figure 5. *Schematic diagram of automatic optimization of fracture prediction parameters at a CRP point.*

3. Application Examples

3.1. Case in Tabei Area

Test area in Tabei is performed high-density full-directional 3D seismic, and target layer is Ordovician Yijianfang Group. It develops fracture-porous carbonate reservoirs and exhibits in seismic as "beaded" reflection (Figure 6). There are two major advantages applying fracture detection based on OVT coil data. On one end, the result demonstrates more details and clearer regional geological pattern. In H7 area, coincident rate between drilling results and fracture prediction using conventional processed data is below 70%. The coincident rate of using data which is processed in six and eighteen directions is 54.4% and 67% respectively. However, it can reach 75% when using OVT data to conduct fracture prediction. On the other end, the prediction result is more conductive in connectivity analysis of fracture cavity system (Figure 7). Fracture detection using conventional data demonstrates that fracture-cavity units in well W1 and W2 are independent to each other, and connected in a large scale. While using OVT domain data shows independence between two wells, but each with a relative limited connective range, which is consisted with the drilling features and production dynamics data. During water injection of well W2, well W1 has no obvious disturbance characteristics, and the oil pressure and daily oil production trend are stable (Figure 8). The crude oil density, oil-gas ratio and H2S content are different for two wells. Crude oil density is $0.877g\cdot cm^{-3}$ (20°C) and $0.884g\cdot cm^{-3}$ (20°C) of W1 and W2 respectively. Oil-gas ratio for W1 is 0.785 while W2 is 0.880. For well W1 and W2, H_2S content is 16300ppm and 18600-19600ppm respectively. Both wells are in production state, and have a low oil pressure of 0.62 MPa and 0 MPa, respectively. Both of them have weak energy and demonstrate as typical fixed-capacity fracture-cavity unit with limited connective range.

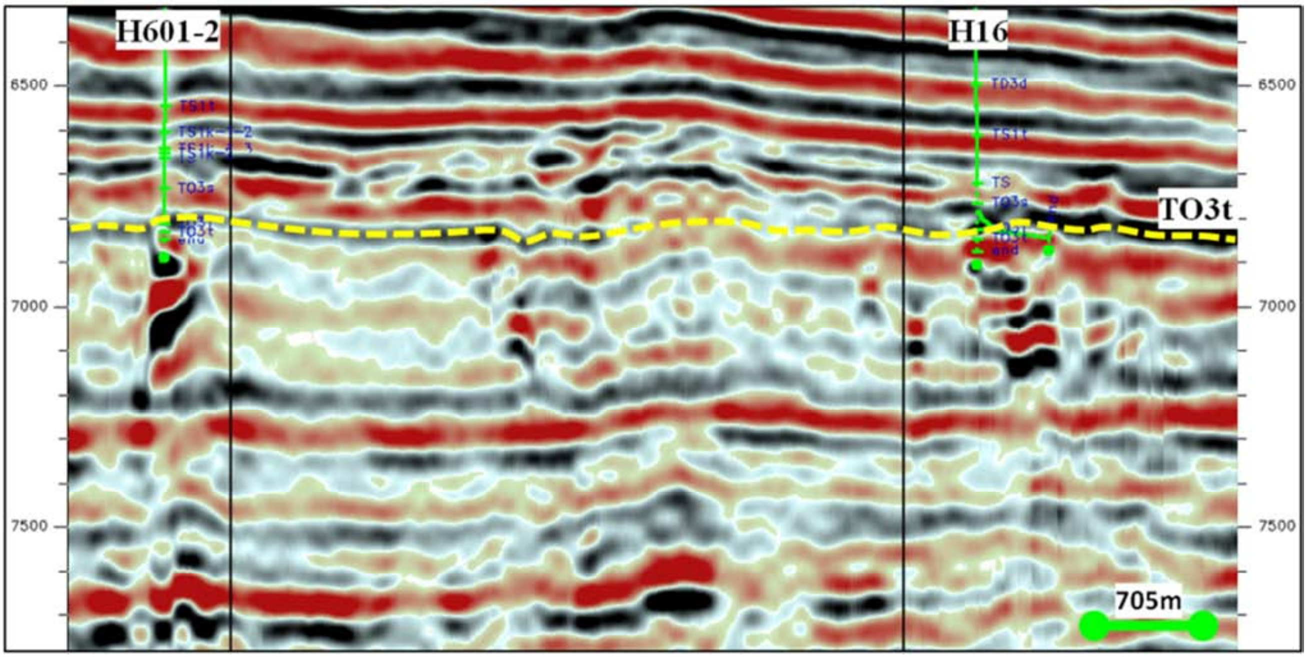


Figure 6. *Seismic profile of well H601-2 well and H16 well of OVT gathers.*

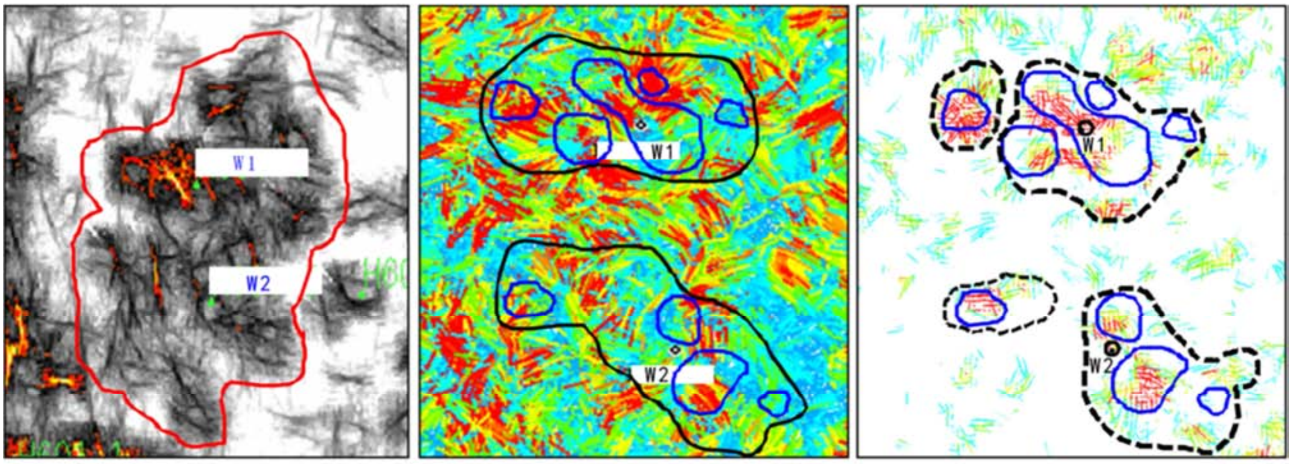


Figure 7. *Comparison of fracture prediction results of different data types in W1 well block.*

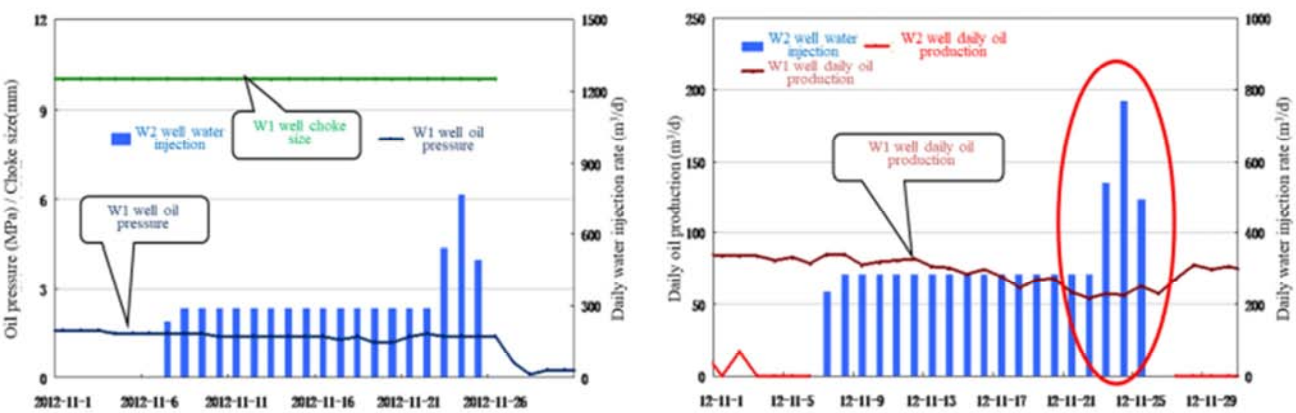


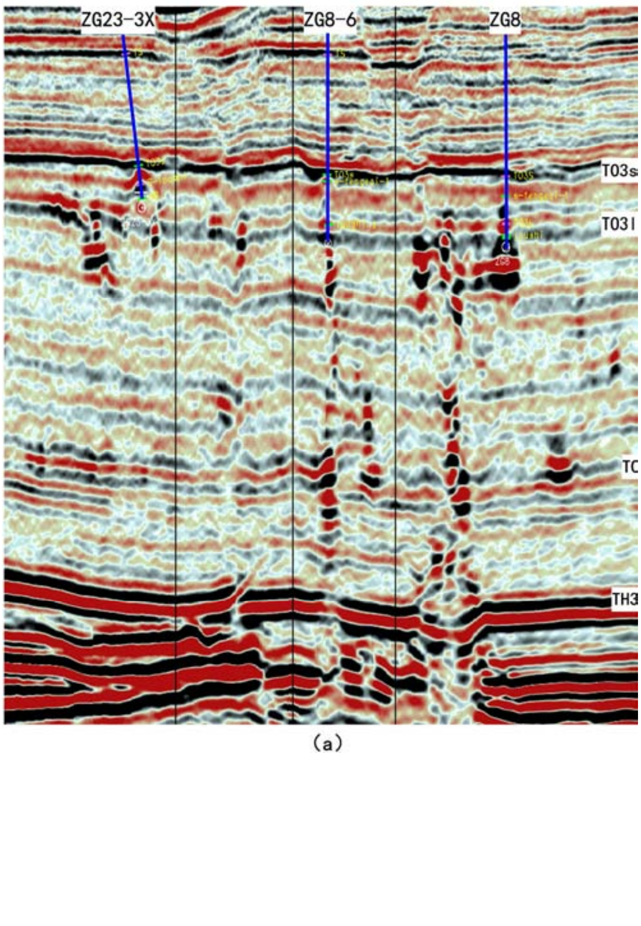
Figure 8. *Interference test diagram of production performance data of W1 well and W2 well.*

3.2. Case in Tazhong Area

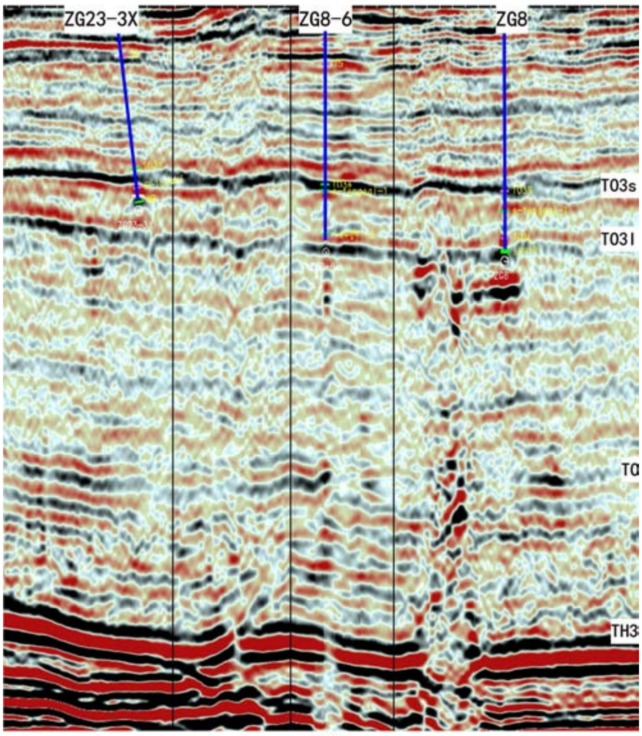
ZG8 3D seismic block in Tazhong area is covered by thick sand dune with an average low-speed belt about 20 m. Target layer is the mid-late Ordovician Lianglitage to Yingshan Formation, which develop heterogeneous fracture-cavity reservoirs. The reservoirs display on seismic as "beaded" reflection (Figure 9). It is the main area of increasing oilfield's development capacity, the target for rolling evaluation of proven reserves, and the crucial area for exploration breakthroughs.

The result is more reliable after applying pre-stack anisotropy fractures detection based on OVT domain data (Figure 10). Fracture prediction result of conventional ellipse fitting method shows fractures are developed in ZG23 block which locates south of ZG11-H1~ZG11-H2 fault zone (zone A in Figure 10a). The result is incorrect comparing to FMI logging interpretation that shows a lack of development of fractures. However, after conducting predictive parameter template auto-optimize method based on RBF neural network using OVT domain data, the fractures' developed direction matches with drilling and FMI logging. The result shows fractures are propagate along the ZG11-H1~ZG11-H2 fault zone and mainly developed in the northern area (zone B), while zone A is lack of fractures (Figure 10 b, c, d, e).

According to statistics, there were 43 wells in study area, 9 of them have FMI logging data. The latest prediction results coincident with 8 of them while conventional results only had coincident rate around 63%. Compared with 39 wells with drilling abnormalities (emptying, leaking, overflowing) or wells confirmed by acid fracturing, the coincidence rate is 94.9% and 82.1% for result using new and conventional methods, respectively.



(a)



(b)

Figure 9. *Comparison of seismic sections of OVT domain processing (a) and conventional processing (b) in ZG8 high density 3D area.*

As showed in figure 11, there are 5 wells (ZG11-H12, ZG11-H5, ZG11-H10, ZG11-H8 and ZG11-6) locates in one fracture cavity unit (Figure 11a). Because of their similar trend of formation static pressure and completely different trend with surrounding wells including ZG11-H7 and ZG11-H1, it can be conclude that they belong to a same pressure system (Figure 11b).

In addition, both ZG11-H10 which in the middle of the five wells and ZG11-6 well that in the northernmost part of the unit show low formation pressure coefficients in the later drilling process, which are 0.89 and 0.85, respectively, indicates the part of the fluid in reservoir has been used. Besides, during the production of ZG11-H10, the deepest well ZG11-H8, which was drilled and produced in the north, immediately showed an increasing water production. Both dynamic and static data indicate that the 5 wells that mentioned above are connected, and further support the fracture prediction results.

The recently deployed wells, ZG11-16, ZG8-H4C, ZG113-1, ZG113-2, ZG8-2X, ZG23-4X, ZG113C, ZG8-7 and ZG8-9 were all tested and put into production, which are consistent with the prediction results and confirm the reliability and high efficiency of the fracture detective method.

4. Conclusions

In summary, through the application of fracture prediction based on the common reflection angle gather has a satisfying outcome. During the connectivity static engrave of large-scale fracture-cavity unit; its assistance restricts the scale of possible connective and fracture-cavity unit. Thus, it provides a more reliable connectivity analysis result in order to support efficient well location deployment and development of reservoirs. The advantages of fracture detection using common reflection angle gather mainly demonstrate in three aspects.

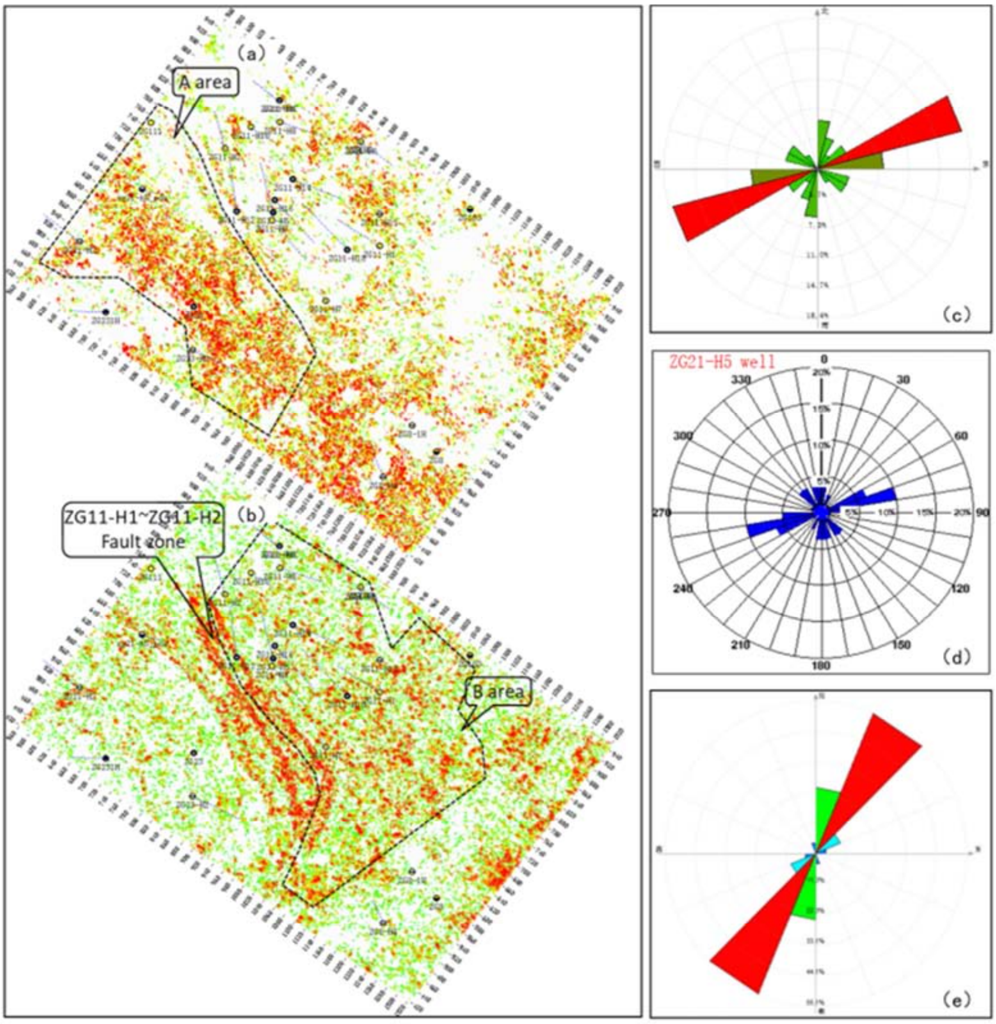


Figure 10. *Comparison of fracture results predicted by new and old methods in ZG8 high density 3D seismic area.*

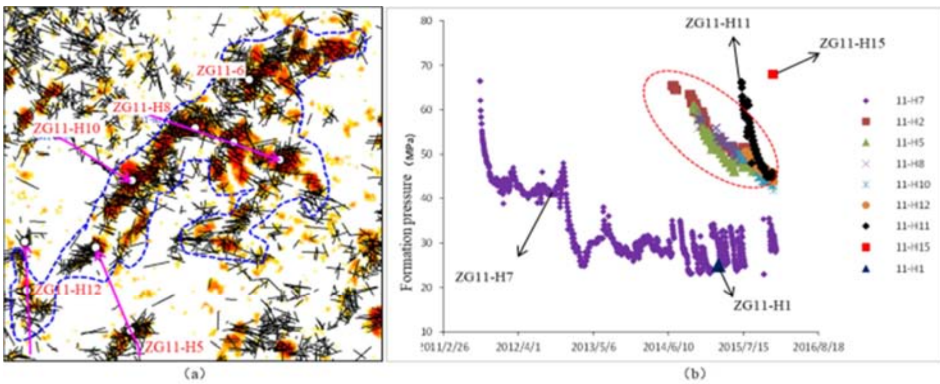


Figure 11. *Fracture prediction and reservoir distribution plane superposition diagram of well ZG11-H8 and other 5 connected units in ZG8 high density 3D seismic area (a) and comparison diagram of multi well formation pressure changing trend with time (b).*

First, the original data maintains azimuth and offset features which benefit the accuracy of fracture detection. Second, based on the GeoEast-EasyTrack interpretation platform, the prediction is not just pure mathematical operation but combined with credibility analysis and quality control, leading to a more detailed result. In addition, with the auto-optimize method of predictive parameter template, it is capable to identify a fracture developed area that consistent with geological understanding.

This method, in one hand, improves the accuracy of complex fracture-cavity feature in low SNR seismic data region. In the other hand, it decrease the time of comparative analysis among various results of parameter schemes and simplify the workflow of fracture detection. Last but not the least, fracture prediction using common reflection angle gather is clearer for revealing geological features, and more consistent with the drilling data, which benefits the connectivity analysis of carbonate rock fracture system.

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