The Application of Full Azimuth 3D Seismic Fracture Detection Technology in the Prediction of Favorable Reservoirs within the Shengbei 5 Well Area Tight Sandstone Region*

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Abstract

Low-permeability hydrocarbon reservoirs within tight sandstones are closely related to the degree of fracturing. Based on wide azimuth seismic data, the density, direction and distribution regularity of reservoir fractures have been predicted using anisotropy detection technology and strain field analysis in the Shengbei 5 Well area. The study results indicate that the fractures are primarily developed adjacent to and sub-parallel with known fault zones in the northern and southeastern regions of the study area. The research results provide reference for well proposals and show that the anisotropy detection technology has a promising application to prospecting based on 3D wide azimuth seismic data.

Introduction

The Shengbei Fault Zone within the Tuha Basin forms a series of near east-trending structures that accommodate north-south directed shortening, which primarily developed due to emplacement of the Yanshannian and Himalayan plutons. The study area is located in the eastern part of the Shengbei Fault Zone where two shallow hydrocarbon reservoirs have been discovered. However, the average depth of the Lower and Middle Jurassic in Yanshan is greater than 4000 m. The main reservoir lithology is composed of fine sandstone with an average porosity of 4-6%, average permeability of less than 0.05 mD, water saturation of ~70%, and has a daily production of ~1500-4500 cubic meters. These properties are characteristic of a tight sandstone reservoir. In order to reduce exploration cost and raise economic efficiency, it is important to be able to predict the location of fractured zones where rich gas reservoirs may exist in tight sandstones.

In this article, fracture development zones are predicted qualitatively and semi-quantitatively by using anisotropy detection technology and wide azimuth seismic data that were newly acquired in 2011. To improve the accuracy of fracture prediction, the analysis of stress field and strain strength was also carried out based on the full azimuth stack seismic data.

Theory of Prestack Seperate-Azimuth Fractures Prediction

Numerous studies conducted by K.L. Craft, S. Mallick and Andreas Ruger indicate that when P-waves propagate through a fractured medium, the variation in amplitude and velocity verses azimuth is a periodic function to the fixed offset. The expression of the P-wave reflection coefficient in fractured reservoir is shown as below：

$$R(\theta,\phi)=A+\left(B^{iso}+B^{ani}\cos^2\phi\right)\sin^2\theta+\left(C^{iso}+C^{ani}\cos^4\phi+C^{ani}\sin^2\phi\cos^2\phi\right)\sin^2\theta\tan^2\theta \qquad (1)$$

where R is the reflection coefficient, θ is the angle between azimuth and fracture trend, Φ is the main fracture development direction, and A is the amplitude.

The gradient of AVO, B is $B^{iso}+B^{ani}\cos^2\Phi$, where B^{iso} is the same in different azimuth, B^{ani} depends on the anisotropic component of the fracture azimuth.

In every CMP gather data, P-wave amplitude and AVO gradient of azimuth can be expressed as the following：

$$A_i=A+B\cos^2\left(\alpha_i-\phi\right) \qquad (2)$$

$$B(\alpha_i)=B^{iso}+B^{ani}\cos^2\left(\alpha_i-\phi\right) \qquad (3)$$

where (i=1, 2, 6, N) is the angle between azimuth and due north.

Therefore, the main fracture development direction (Φ) can be obtained through the least square fitting of amplitude and the AVO gradient on each seismic azimuth. The density of fracture development can be obtained through parameters B and B^{ani}.

When underground belts of parallel vertical or nearly vertical fractures exist, amplitude, frequency and velocity of vertical and horizontal seismic wave propagation will be affected by the fractures. Theoretical studies show that the influence of fractures may reach a maximum in the dip direction, and a minimum in the strike direction (Figure 1). P-wave anisotropy fracture detection is carried out by using seismic attributes of different azimuth during ellipse fitting. Compression of the oval represents fracture density, whereas the long axis of the oval corresponds to the fracture trend (Figure 2).

Based on the feasibility analysis of pre-stack seismic data, several azimuth seismic data with sensitive attributes of reservoir fractures were extracted. The "ellipse", azimuth seismic attributes are fitted by using fracture analysis and calculations based on related software. The ellipse oblateness is defined as the ratio of the long axis to the short axis. The value of the ratio reflects the anisotropy strength when seismic waves propagate through a fractured medium of reservoirs. The anisotropy strength is related to the fracture density. When fracture density is large, the anisotropy strength is also large. The relative development degree of reservoir fractures can be detected quantitatively through the anisotropy strength analysis. Simultaneously, the orientation of reservoir fractures can be detected through the analysis of ellipse azimuth fitting in each CDP based on the forward modeling results of rock physics model.

Feasibility Analysis of Fracture Prediction in Shengbei 5 Well Area

The fracture detection technology of wide azimuth 3D seismic is based on the amplitude information of different offset and azimuth, therefore it is required that the original data acquisition have high folds based on the high S/N ratio. The data also needs to have a uniform distribution of offsets and azimuths. The folds of the Shengbei area are relatively higher than the other areas, and the distribution of offsets and folds are uniform (Figure 3), the horizontal-to-vertical proportion approaches 1.

The data processing is carried out for the geological needs of fracture detection. The workflow and parameters of separate-azimuth procession are determined based on the relatively uniform distribution of folds and offsets in all separate-azimuth data. The resulting seismic data are then divided into 4 separate-azimuth datasets (each one is 45°) after the static and NMO correction with each separate-azimuth data are resolved to verify that the data fidelity and amplitude are preserved. From the physical attribute analysis of four separate azimuth data, the maximum peak amplitudes of different data are significantly different (Figure 4), and the anisotropy of different azimuth data provides a basis for fracture prediction.

Pre-stack forward modeling of the reservoir fractures is beneficial to understand the relationship of fracture density, direction and fluid property with AVO response, in addition to being used to guide the extraction and analysis of azimuth seismic attributes. First the trend angle is assumed to be 90° (North-South direction), which is used to contrast with azimuthal ellipse fitting of target layers of drilled wells, and to determine the input model of fracture calculation analysis. Then using the forward modeling software of rock physics, the actual ellipse of azimuth amplitude is fit. According to the theory of seismic wave propagation, the longer axis of azimuth amplitude ellipse represents the development direction of fractures, whereas the shorter axis represents the dip direction of fractures.

Figure 5 shows the rock physical forward modeling result of azimuth anisotropy in the condition of gas saturation of reservoirs. Amplitude decreases with increase of offset (incident angle) in the same azimuth of the gas layer. For the same incident angle, the amplitude of 0° is greater than 90° (yellow curve) (Figure 5, middle, right upper), which indicates that the shorter axis of azimuth amplitude ellipse represents the fracture trend (Figure 5, middle, lower right). From the forward modeling attribute analysis of the original seismic data and well data, the anisotropy characteristics of wide azimuth seismic data are clear. The AVO characteristics along with azimuth variation are also clear. So it is considered that the fracture prediction method is feasible based on the wide azimuth seismic data.

Analysis of Strain Field

To some extent, the stress field represents the strength and direction of strata deformation. For brittle strata, the distribution characteristics of the strain field represent the development of faults and fractures. The modeling technology of the stress field primarily uses the geology, drilling and well logging data, and the use of elastic inversion to invert the Lame constant and shear modulus to build geologic, mechanical, mathematical models. These models can be applied to the 3D finite difference numerical simulation method to simulate the stress field, research the relationship of fractures distribution and geologic factors such as structure, faulting, formation thickness and regional stress field, and to predict the distribution and degree of fracture development related to the structures. It is assumed that the studied strata are uniformly continuous, isotropic and completely elastic, so the form of the strata is considered to be completely developed in response to structural stresses. Therefore, the fracture prediction results of the stress field usually have large errors or multiple solutions. So caution is needed when applying stress field analysis to predict fractures and it is suggested that stress field analysis be combined with other methods to reduce errors and improve the reliable precision of fracture prediction. Figure 6 shows the modeling results of the structural stress field, where the fractures trend northwest (red and yellow represent fracture zones) and are developed adjacent to the faults.

Analysis of Fracture Prediction in Reservoirs

In this article, through the optimization of methods and parameters, the fracture directions are predicted using the impedance attributes of pre-stack data (Figure 7, the trend of roses represents the direction of fractures), and the fracture density is predicted by using the frequency attenuation attributes of pre-stack data (Figure 8, the colors of red and yellow represent the developed zones of fractures). The fracture prediction technology is based on the anisotropy characteristics of seismic waves within the Shengbei 5 Well area. The application results indicate that the development of fractures in the West-1 reservoir are primarily East-West trending. Shown with the overlap map of fracture density and structure, the development of fracture zones are primarily located on the two limbs of the southern and northern structures adjacent the faults. In contrast, fractures are poorly developed in the axis of structure.

The development degrees of fractures are regional, the highly fractured zones are primarily located on the southern and northern part, the fractures are distributed intensively in the two limbs of the anticlines where stress is concentrated and the strain degree is greater than within the axis of the anticline. This is likely a function of extrusion structural stress oriented in a North-South direction.

Through the analysis of structural stress, the fractures are seen to develop in a Northwest trend, which is consistent with the trend of major faults in the area. However, results based on the pre-stack impedance attributes analysis indicate that the directions of fractures are near East-West trending, and therefore the results of the two different methods appear to conflict. At present, the relative error of stress field modeling results is greater than the pre-stack impedance method. Therefore, the structural stress analysis is mainly used to check whether the study area has the structural background for fracture development. Since the fracture development directions are mainly predicted by the method based on the characteristics of seismic anisotropy, we found that the fracture directions of the West-1 reservoir are primarily oriented approximately East-West.

Conclusions

The fracture prediction method, which is based on the anisotropy characteristics of seismic waves, requires full (or wide) azimuth seismic data, and that the distribution of folds and offsets is as uniform as possible. When processing the seismic data, it is strictly required that high fidelity and good amplitude are preserved, otherwise it will limit the practicability of this method. Compared with the prediction method of the structural stress field, the fracture prediction technology based on wide azimuth 3D seismic data makes full use of azimuth anisotropy characteristics of fractures, and can predict the fracture development zones effectively.

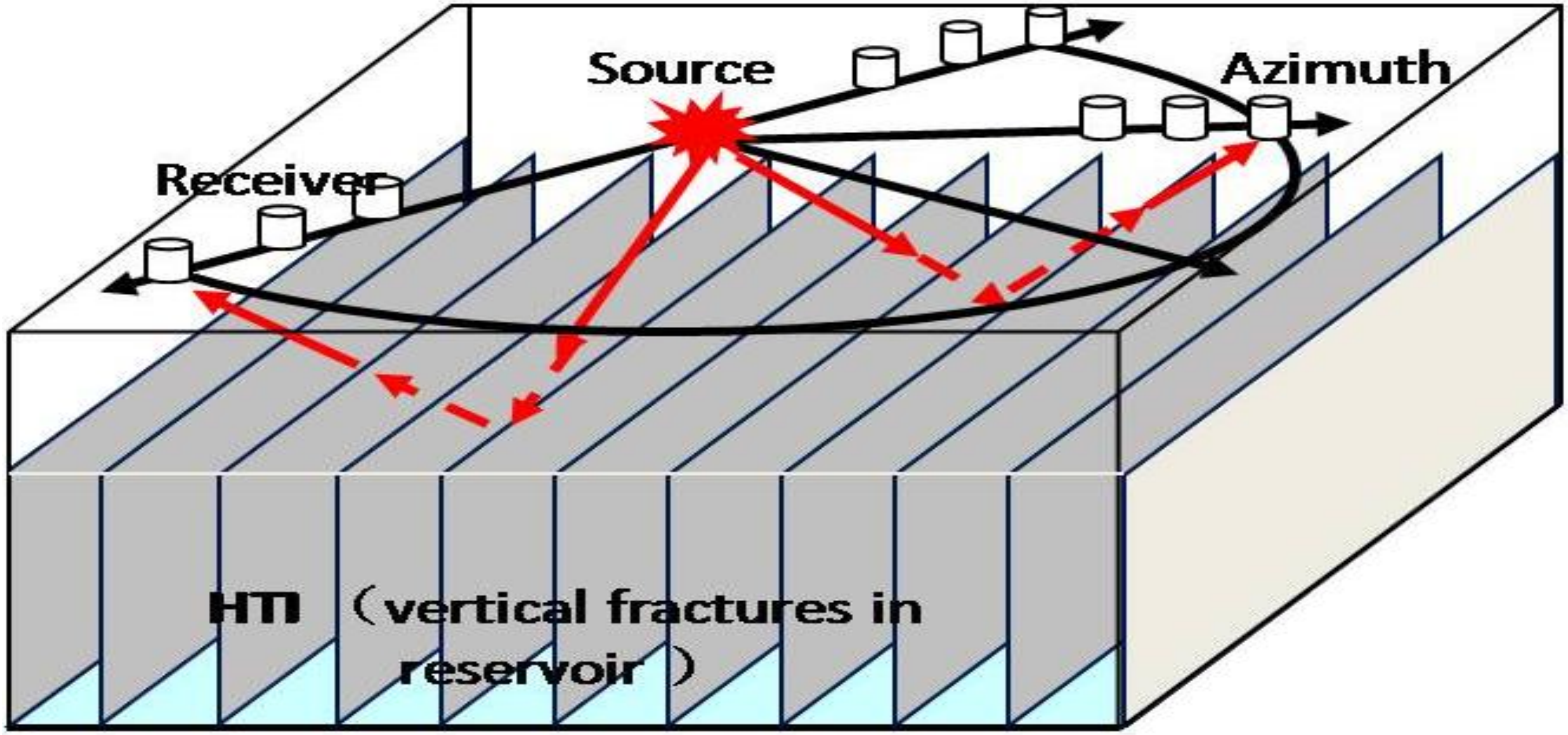


Figure 1. Vertical fractured reservoir and 3D seismic azimuth data acquisition scheme.

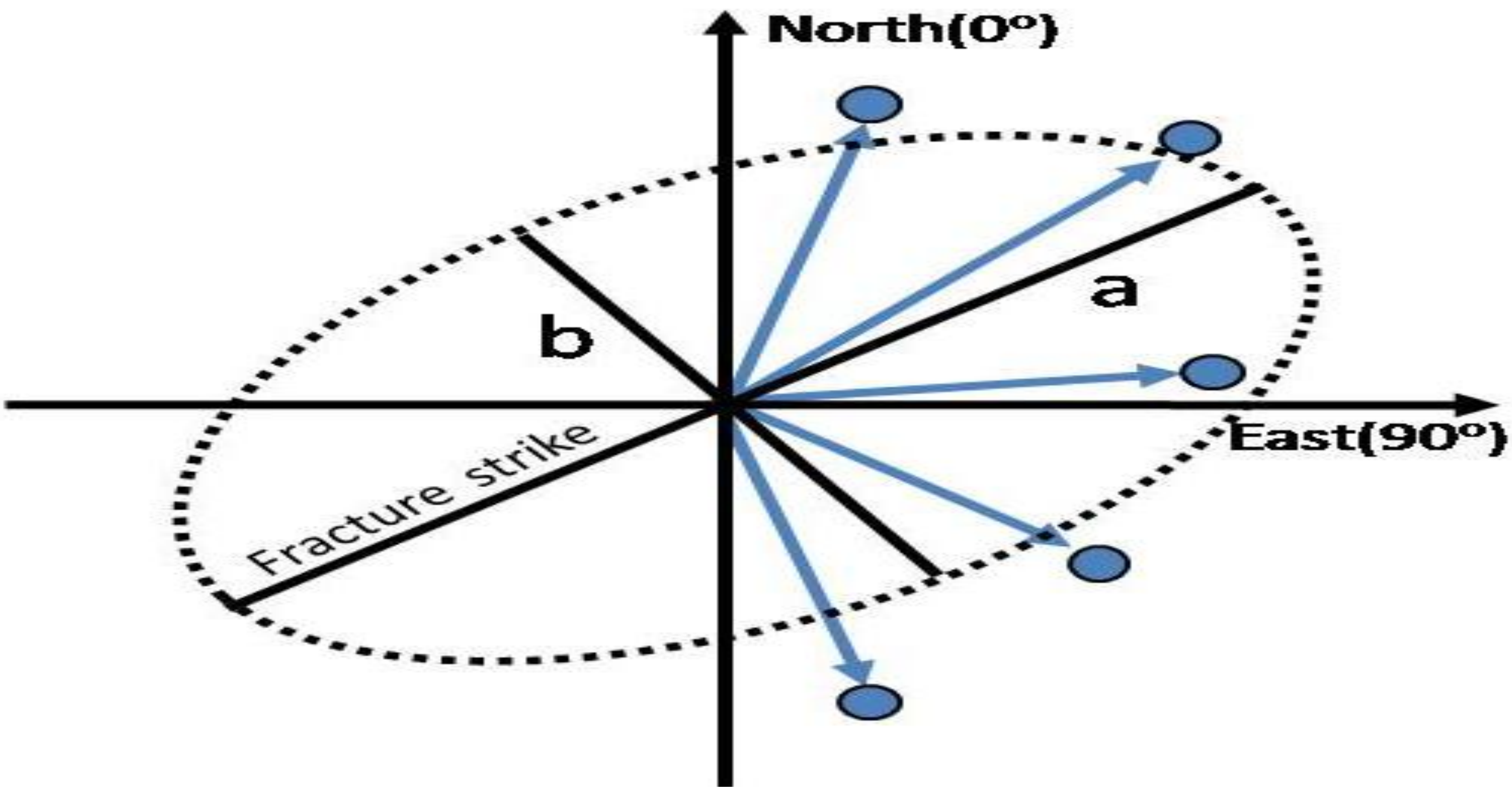


Figure 2. An ellipse-fitting method for the fracture prediction diagram.

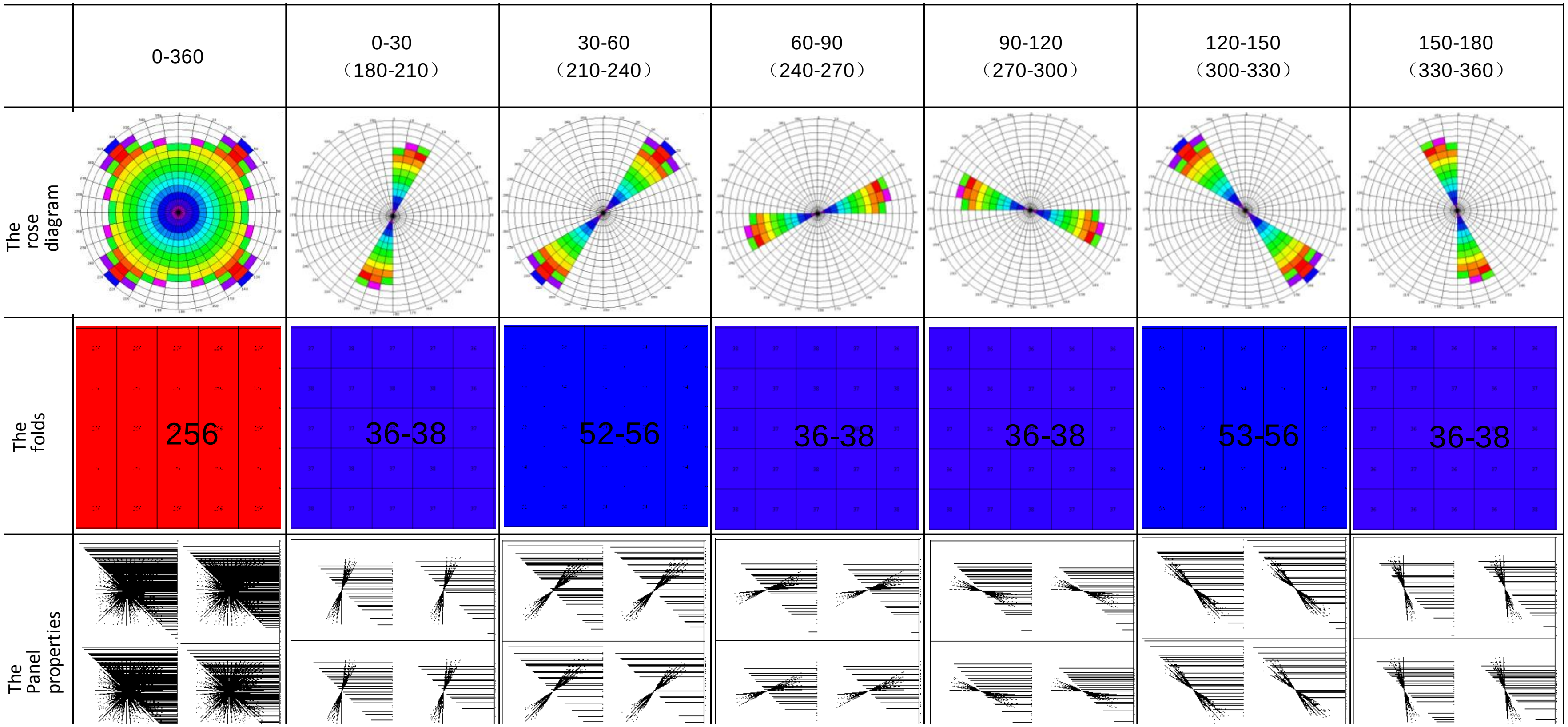


Figure 3. Shengbei area wide azimuth 3D observation system attributes.

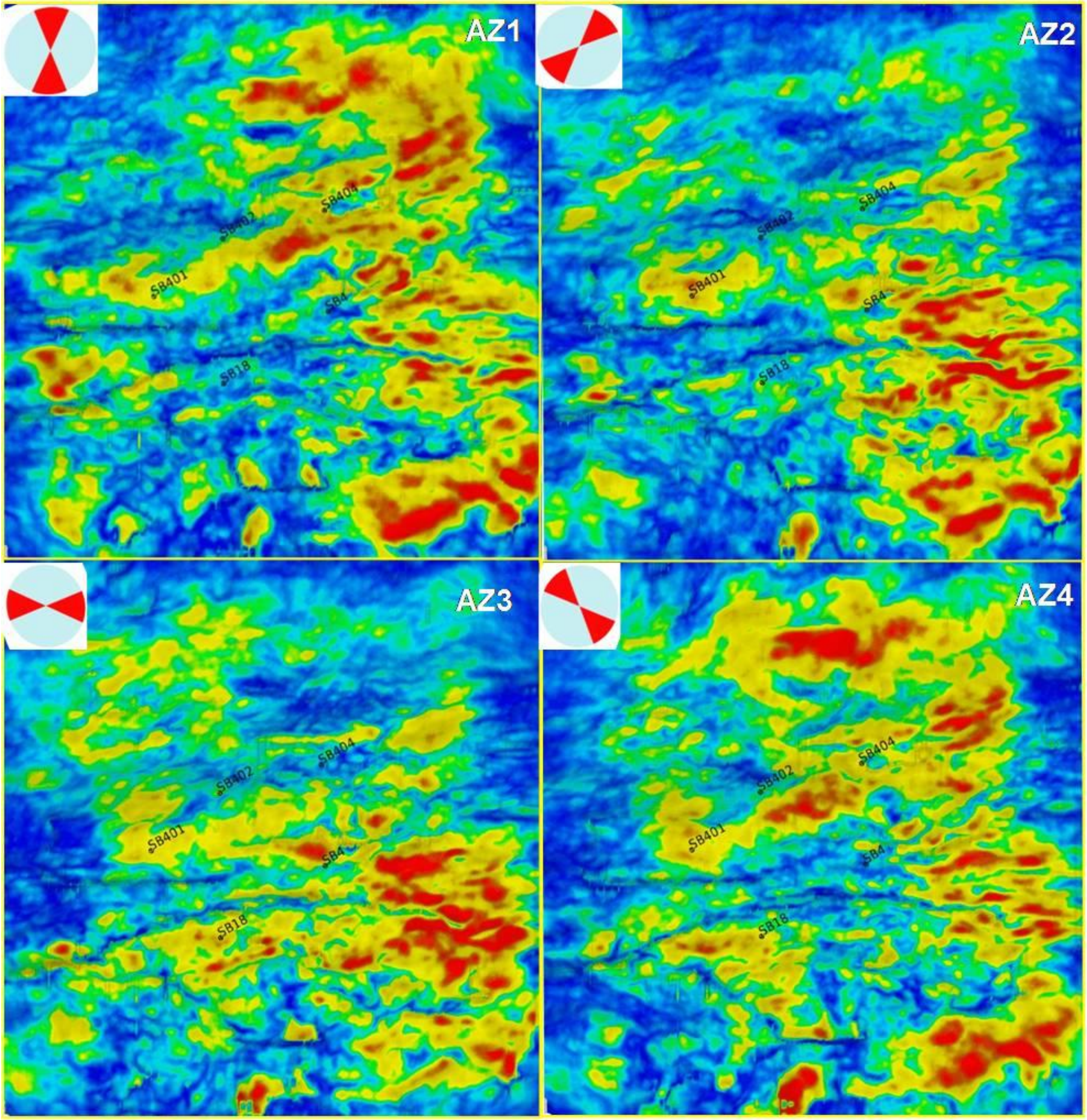
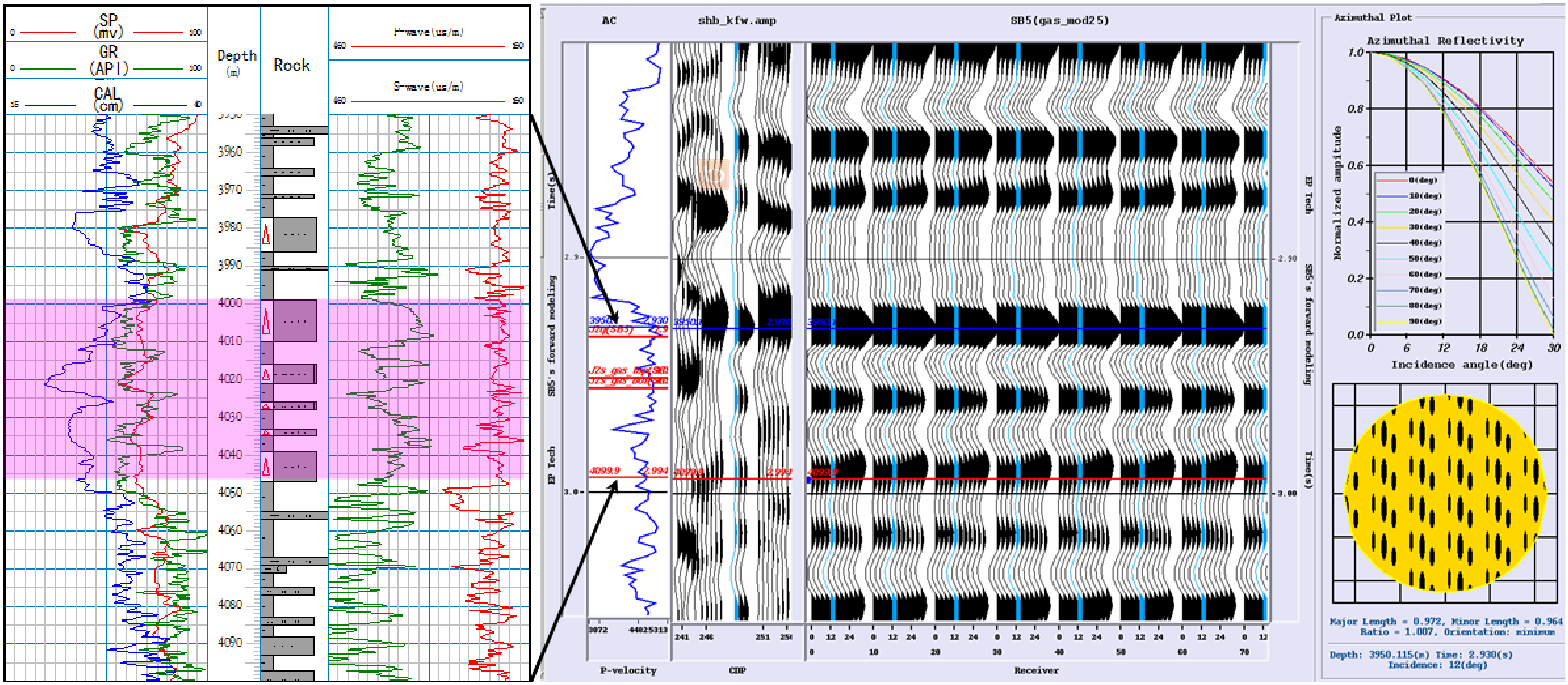


Figure 4. Planar graph of the maximum peak amplitude along the J_2x layer.



(a) (b) (c)

Figure 5. Forward modeling result of AVO with azimuth variation in target layers. (a) Well logs, (b) forward modeling gather of separate azimuth, and (c) the result of AVO with azimuth variation and ellipse fitting.

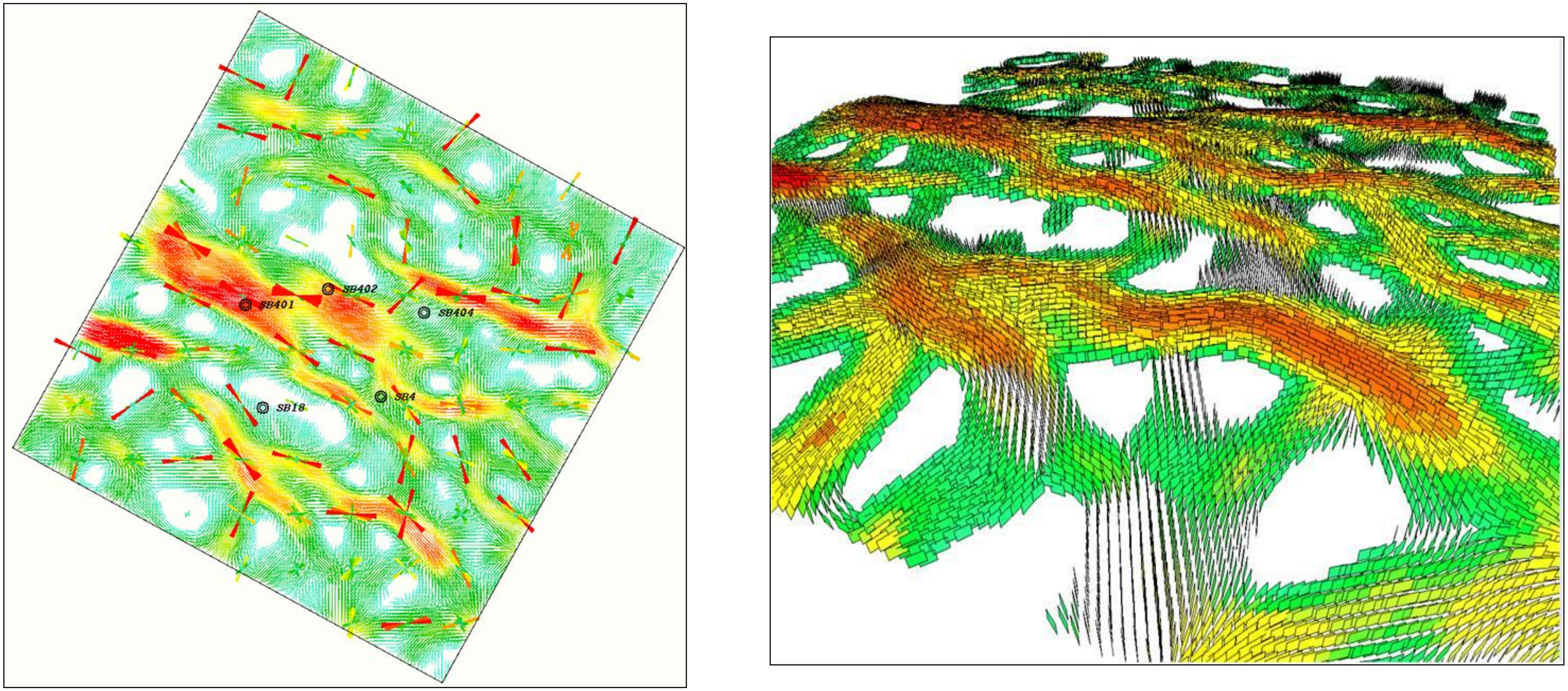


Figure 6. Simulation result of structural stress field in Shengbei area. (Left) Rose diagram of strain direction in West-1 reservoir; (Right) 3D display of fracture trend in West-1 reservoir).

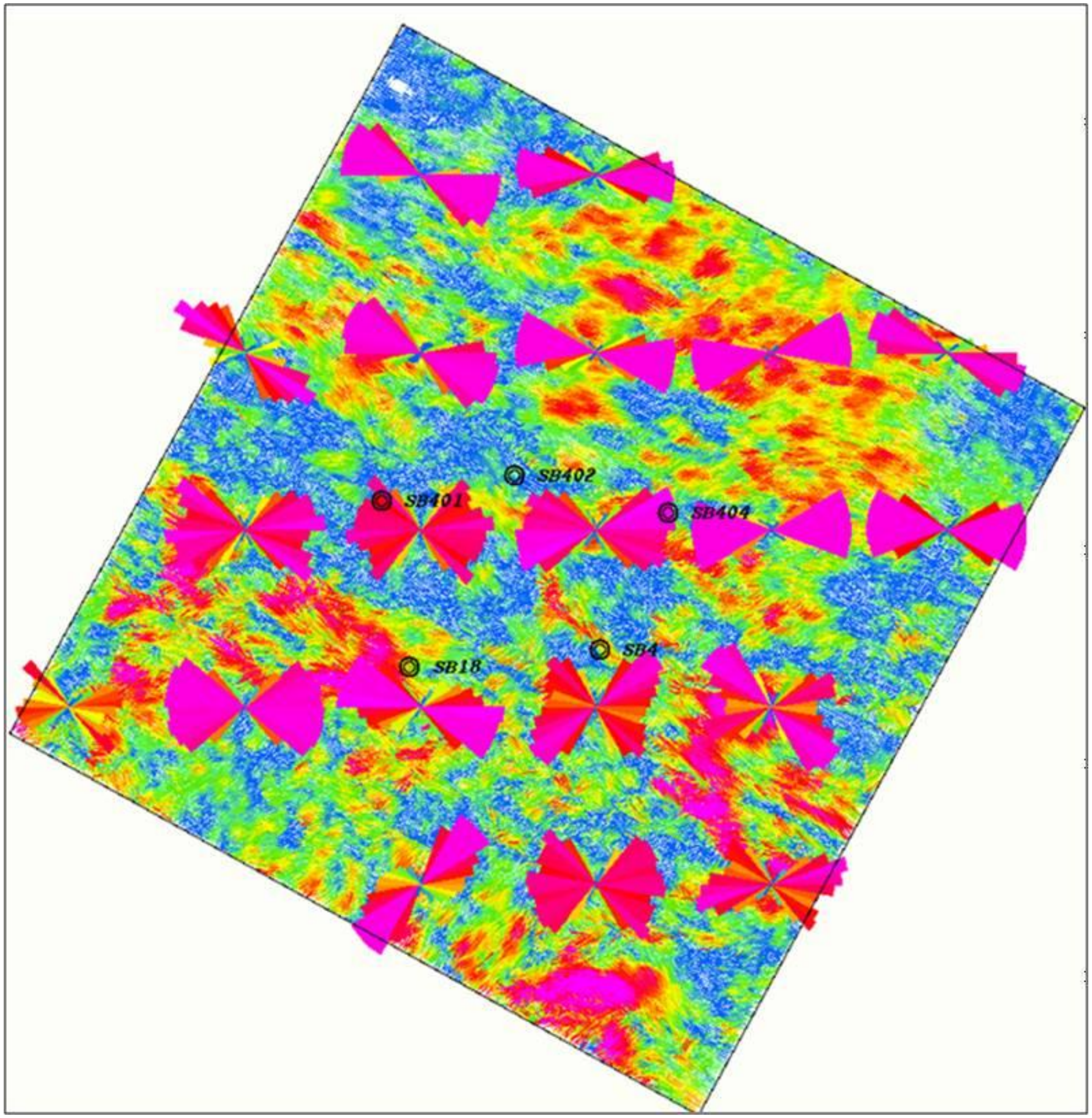


Figure 7. The plan view of fracture directions in the West-1 reservoir.

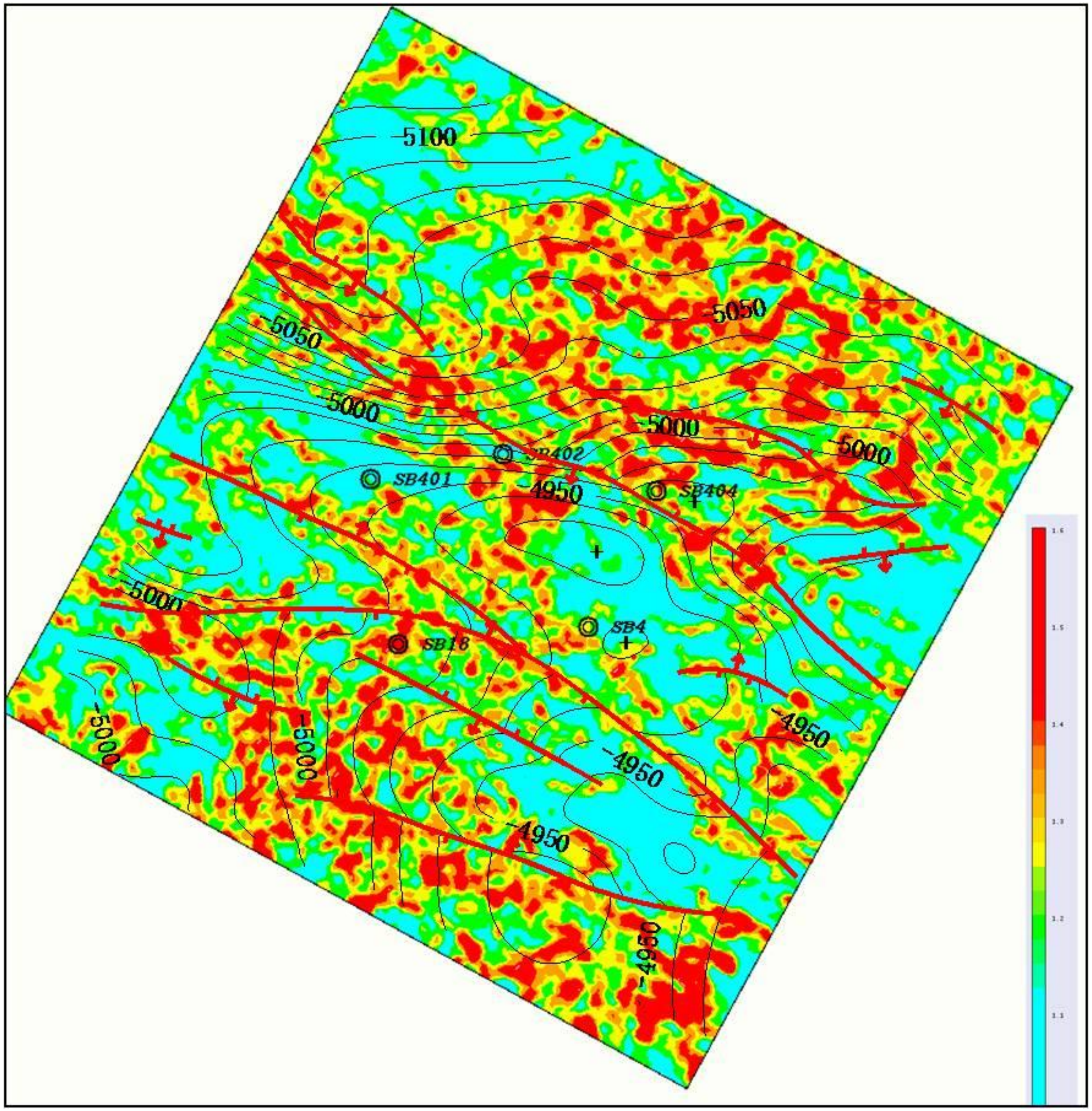


Figure 8. The overlay map of fracture density and structure in West-1 reservoir.