Multi-scale fracture prediction using P-wave data: a case study

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Summary

Fracture prediction is very difficult when characterizing unconventional hydrocarbon reservoirs, especially for reservoirs with different fracture scale sizes. Here, we present an integrated workflow combined with poststack and prestack seismic attributes to distinguish between fractures of different scale, which is used in a case study from a basin in China. We classify fracture scales into three categories: macro-scale, meso-scale and micro-scale. In this case study, we used poststack seismic attributes to predict the macro-scale fractures, and utilized prestack seismic inversion to determine the meso-scale fractures. Micro-scale fracture prediction is out of the range of this study. We combined the prediction results with the superimposed images of faults, verified the corresponding relation between meso-scale fractures and faults, and finally comprehensively analyzed the fracture development of the target horizon. The integrated prediction result indicates that the structure of the target horizon is mainly controlled by several major faults and meso-scale fractures are distributed along the fault zones.

Introduction

As a type of unconventional hydrocarbon, coalbed methane is one of the most important supplements to conventional oil and gas, and plays an important strategic role. It is important for the exploration and development of coalbed gas reservoirs that research is directed to features leading to the accumulation and enrichment of coalbed methane. There are abundant coalbed methane resources in our study area in China. As fractures provide the main storage space for gas in coal seams, it is vital to do research on fracture prediction for the detection of accumulations of coalbed methane.

Currently, the main geophysical methods for fracture prediction are P-wave detection, S-wave detection, converted wave detection and multiwave multicomponent seismic technology, etc. To predict fractures using P-wave seismic data is an economical and feasible method (MacBeth and Li, 1999). Recently, fracture prediction using P-wave azimuthal AVO is becoming a research hotspot (Mallick et al., 1991; Gray et al., 2004). However, these successful methods are mostly applied to oil and gas reservoirs, while rarely applied to coal seams. Here, we predict the fracture development of the target horizon in coal seams comprehensively, by combining P-wave azimuthal AVO with poststack seismic attributes and well logging data.

Method and Theory

According to MacBeth and Li (1999), fractures can be classified into three scales depending on their length: 1) macro-scale fractures such as faults, which are greater than one-quarter wavelength and identifiable in a poststack seismic profile; 2) meso-scale fractures such as cross-bedding, which are less than one-quarter seismic wavelength and greater than one percent seismic wavelength, and can't be identified in a poststack seismic profile; 3) micro-scale fractures, which can only be observed by electron microscope.

Generally, macro-scale fractures can be well characterized by poststack seismic attributes such as coherence, curvature and so on. However, prestack seismic data is necessary for predicting meso-scale fractures, which cannot be identified in a poststack seismic profile. In actual reservoirs, vertical meso-scale fractures are easily produced by the effects of formation pressure, so that the layer shows anisotropic characteristics. In the horizontal plane, the azimuthal variation of prestack seismic attributes, such as traveltime, attenuation, amplitude etc. can be approximately described by an ellipse. At least three data points are needed to define an ellipse in the plane of azimuthal variation. Therefore, in order to extract the meso-scale fracture information, wide azimuth angle prestack 3D P-wave data is required (Li et al., 2003). For the anisotropic ellipse, the long axis indicates the fracture orientation, and the relative ratio of the long to short axes is proportional to the fracture density. According to the approximate P-wave reflection coefficient for interfaces between horizontal transverse isotropy (HTI) media proposed by Rüger (1998), we can derive the orientation and density of fractures by ellipse fitting based on the amplitude variation with incident angle and azimuth angle.

In our study, the main aim is to determine the fracture development of the target coal seam. Our proposed workflow includes macro-scale fracture prediction based on poststack seismic attributes, and meso-scale fracture prediction based on prestack seismic attributes and fusion of multiple attributes, as shown in Figure 1.

Study area overview

The structure of the target study area is relatively simple. Folds are the major structures and take the form of flattened waves. A small number of faults and collapsed columns are growing while secondary cleats are well developed in the coal seam.

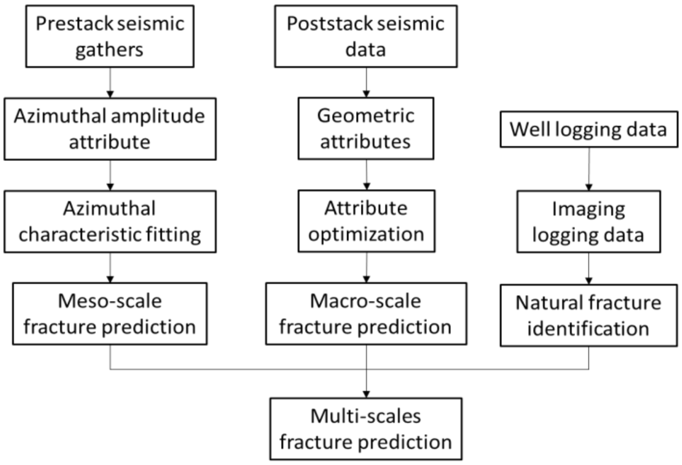

Figure 1 *The procedure for integrated multi-scale fracture prediction with prestack and poststack seismic and well logging.*

Macro-scale fracture prediction by poststack seismic attributes

Firstly, we use poststack seismic attributes to predict macro-scale fractures. In order to predict the faults and macro-scale fractures, we analyse a series of poststack seismic geometric attributes, such as coherence, curvature, variance and so on. By means of attribute optimization, we choose to describe the distribution of faults with the coherence attribute, and characterize the development of folds with the curvature attribute. Figure 2 shows the coherence attribute slice extracted along the target horizon. The result indicates that the faults are mainly stripe-shaped in the north-south direction and the faults are mostly located at the eastern part of the study area while hardly developed in the western part. Figure 3 shows the curvature attribute slice extracted along the target horizon. The result indicates that the folds are mostly dominated by an anticline and a few synclines are also present. Taken together, these folds control the distribution and development of faults in the study area. We can suggest that macro-scale fractures are mainly fault broken zones, supplemented by fractures produced by the bending of folds. Due to the fact that meso-scale fractures cannot be distinguished in the poststack seismic profile, prestack seismic data is required to predict meso-scale fractures.

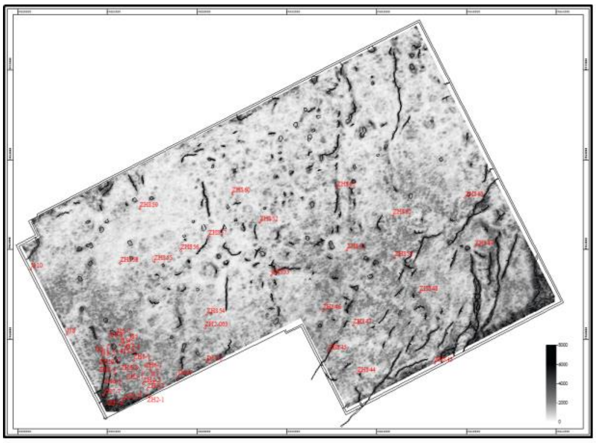

Figure2 *Coherence attribute of the target horizon.*

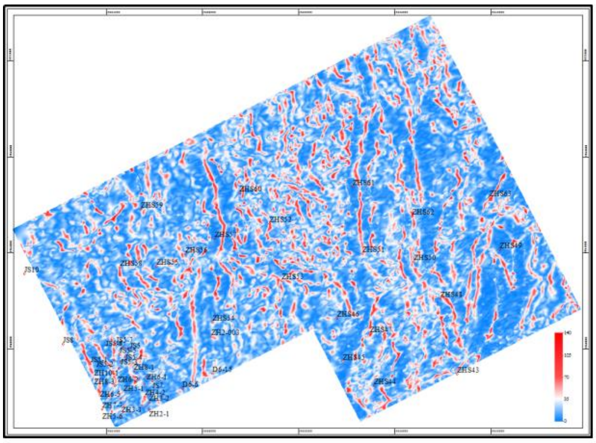

Figure3 *Curvature attribute of the target horizon.*

Meso-scale fracture prediction by prestack seismic attributes

Secondly, we use prestack seismic attributes to predict meso-scale fractures. Figure 4 shows the offset-azimuth cross plot of prestack gathers, which demonstrates that the prestack seismic data has sufficient azimuthal coverage for meso-scale fracture prediction. In order to obtain the prestack P-wave attribute variation with azimuth angle, we divide the data into five azimuthal bins with 50° bin size, perform stacking, and get five narrow-azimuth data volumes. In the process of narrow-azimuth stacking, we cut off the far-offset data to eliminate the effects of different folds on different azimuth gathers.

For the five data volumes obtained by narrow-azimuth stacking, we derive incident angle information from velocity analysis, perform AVAZ inversion based on the azimuth angle, incident angle and amplitude information, and finally obtain the density and orientation volumes of fractures. Figure 5 and 6a show the density and orientation respectively of fractures extracted along the target horizon. We can see that fractures are well developed in the eastern area where faults grow well, while few fractures are distributed in the western area where faults are hardly developed. The result demonstrates that the development of meso-scale fractures is dominated by the distribution of faults. Comparing Figure 6a with the rose diagram of fracture orientations obtained by image logging interpretation (Figure 6b), their consistency indicates that the fractures of the target horizon are mainly in the directions N30°E and N60°W.

Integrated interpretation

Finally, we superimpose the results predicted by multiple attributes. In Figure 7a, we superimpose the poststack coherence attribute (in grey) on the fracture density slice predicted by prestack amplitude attribute (in color). The fractures are mostly located on the two flanks of faults along the fault strikes, which demonstrates that faults control the development of fractures in the target horizon. In Figure 7b, we superimpose the poststack curvature attribute (in blue) on the fracture density slice predicted by prestack amplitude attribute (in red and yellow). We can infer that fractures are controlled by faults while faults are dominated by folds.

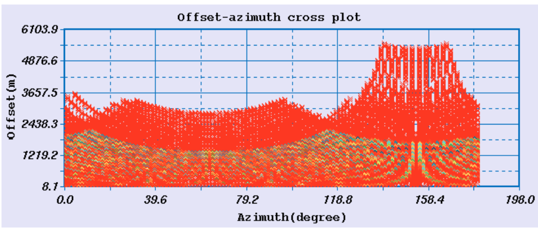

***Figure 4** The offset-azimuth cross plot of prestack gathers.*

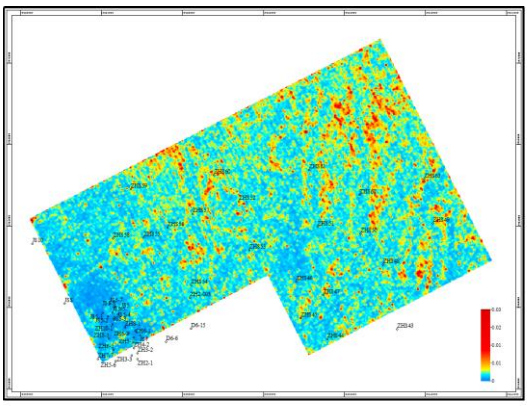

***Figure 5** Estimated fracture density of the target horizon using prestack amplitude attributes.*

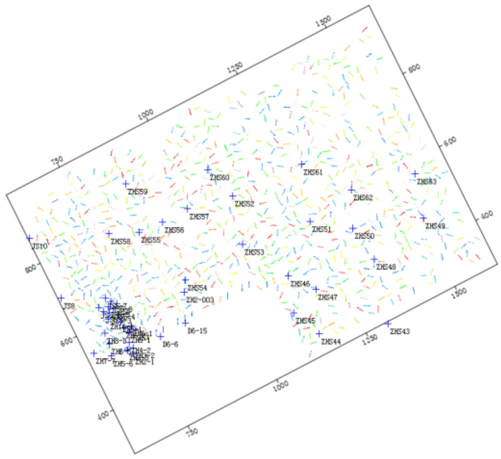

***Figure 6a** Estimated fracture orientation of the target horizon using prestack amplitude attributes.*

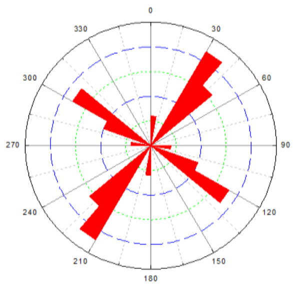

***Figure 6b** Rose diagram of fracture orientations by image logging interpretation.*

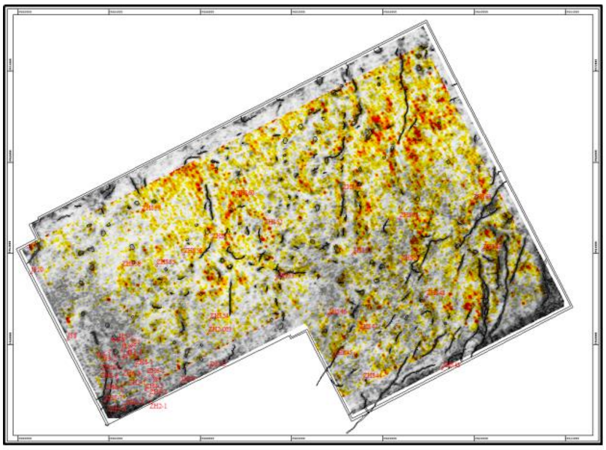

Figure 7a *Coherence attributes in grey, superimposed on fracture density predicted by prestack amplitude attribute in color.*

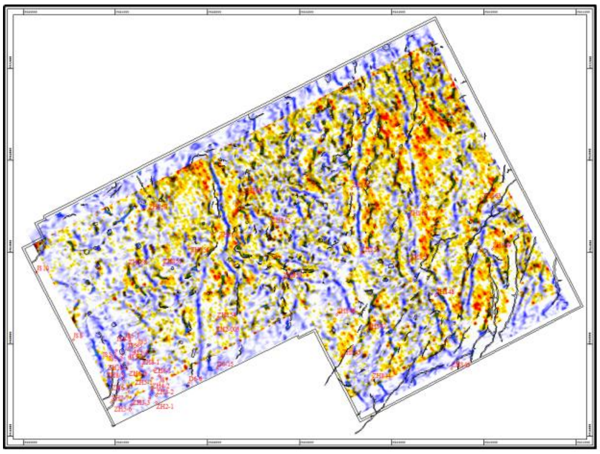

Figure 7b *Flexure attributes in blue, superimposed on fracture density predicted by prestack amplitude attribute in red and yellow.*

Conclusions

We have developed a systematic procedure for multi-scale fracture prediction and carried out a case study using P-wave seismic and well logging data. We describe the distribution of folds using a poststack curvature attribute, characterize the macro-scale fractures which are associated with faults by a poststack coherence attribute, and predict the development of meso-scale fractures with a prestack amplitude attribute. We perform an integrated fracture prediction by superimposing the multiple poststack and prestack attributes. We confirm the correctness of the integrated prediction result by combining with the rose diagram of fracture orientations obtained by image logging. In the target horizon of the study area, macro-scale fractures are mainly fault broken zones, supplemented by fractures produced by the bending of folds. Meso-scale fractures are mostly located on the two flanks of faults along the fault strikes, which indicates that the development of meso-scale fractures is dominated by the distribution of faults.

Acknowledgements

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