An integrated study of fracture detection using P-wave seismic data

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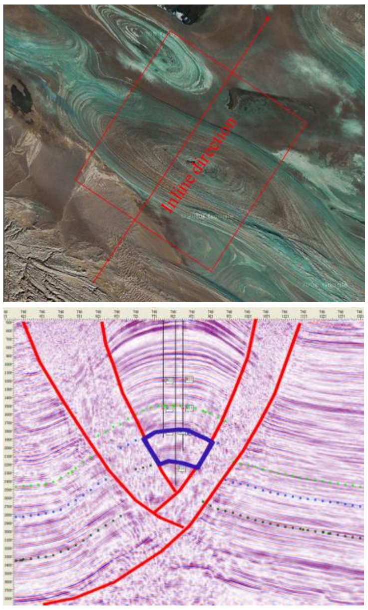
Summary

We present an integrated study of fracture detection by analyzing the seismic anisotropy in the 3D P-wave seismic data from Caidamu Basin in Northwest China. The study area lies on a big anticline which runs from southeast to northwest with the area around 400 km^2, and each flank of the anticline develops a reverse fault. The target layer is a fractured gas reservoir at a depth of around 3 km just under the anticline. We first study the fracture characteristics from outcrop analogues, core samples and well logs. We then analyze the coherence and curvature attributes from post-stack seismic data, and azimuthal variation of amplitude and traveltime from pre-stack seismic data. After a careful and integrated analysis, we find that fractures are widespread and regularly distributed in the middle of study area along the anticline strike, and form good pathways and store space for fluid. The final results estimated using azimuthal analysis of pre-stack seismic amplitude data are consistent with results of core and log analysis at the well locations, which extended our knowledge of the fracture distribution in the reservoir.

Introduction

Using P-wave seismic data to predict the fracture parameters is an economical means to characterize fracture reservoirs, and it has gradually gained geophysicists' acceptance since the end of last century (MacBeth and Li 1999; Gray et al., 2002). Theoretically a fracture reservoir embedded in an isotropic background is often equivalent to an anisotropic medium whose symmetry depends on the fracture orientation, and the P-wave reflection amplitude at the top of fracture reservoirs often shows an elliptical variation in the horizontal plane, i.e., azimuthal anisotropy. In practice, a number of factors may affect the seismic amplitude, introducing large uncertainties in fracture estimation using azimuthal AVO analysis. In order to reduce uncertainties in seismic data, The scheme of prestack seismic analysis is often combined with the analysis of other available geological and geophysical information.

In this paper we give an integrated case study of fracture detection with P-wave seismic data from Caidamu Basin in Northwest China, which is a semi-desert region (Figure 1a). The study area consists of a big anticline running from southeast to northwest, formed due to the compression from its two flanks with the reverse faulting structure at each flank location. Meanwhile, intensive fracturing occurred during this process. This structural setting and the resulted fracturing provided a perfect space for moving and storing fluid (Figure 1b). The actual study area covers 400 km^2. The target layer (named L1, as shown in the blue closed line in Figure 1b) is a fractured condensate gas reservoir just under the anticline. The reservoir is at the depth of around 3km, and consists of mudstone and limestone. The main task in this study is to predict the fracture parameters with the theory of azimuth anisotropy, the integration of all other available data in the study area, including outcrop studies, core and log analysis, and pre- and post-stack seismic data analyses.



(a) (b)

Figure 1. *(a) Google map view from the space; (b) a seismic section running through the anticline with the anticline in the middle, two reverse fault zones (between the two set of red lines) at the flanks, and the target reservoir just beneath the anticline (in blue closed line).*

Outcrop, core and log interpretation

Investigation of outcrops, microscopic rock slice and core samples is a visual and direct way to observe the geological features of the target region. In this study the investigation of the outcrops is performed in many different locations (Figure 2a, 2b, 2e) on the top of the anticline. The rose diagrams (Figure 2e) show that the orientation of 70% fracture aligns parallel to or perpendicular to the anticline strike. Small fractures or cracks, and micro cracks can be observed from core samples and microscopic rock slices. The observation of the core samples (Figure 2c) from 8 wells in the study area shows that small fractures develop on both vertical and horizontal directions, and these fractures form the main pathways and store space for fluids. Micro cracks can only be observed through microscope from the microscopic rock slices (Figure 2d). The average aperture of the micro cracks observed is less than 40 um, which is also important for fluid storing and flowing through. All the observations reveal that fractures are widespread and regularly distributed in the surface and in the target reservoir. It is seen that there is a good correlation between the fracture in the cores and the gas production. Well 4 (shown in Figure 2e) is chosen to test the fracture development at the location with the image logging (FMI) method in Figure 2f.

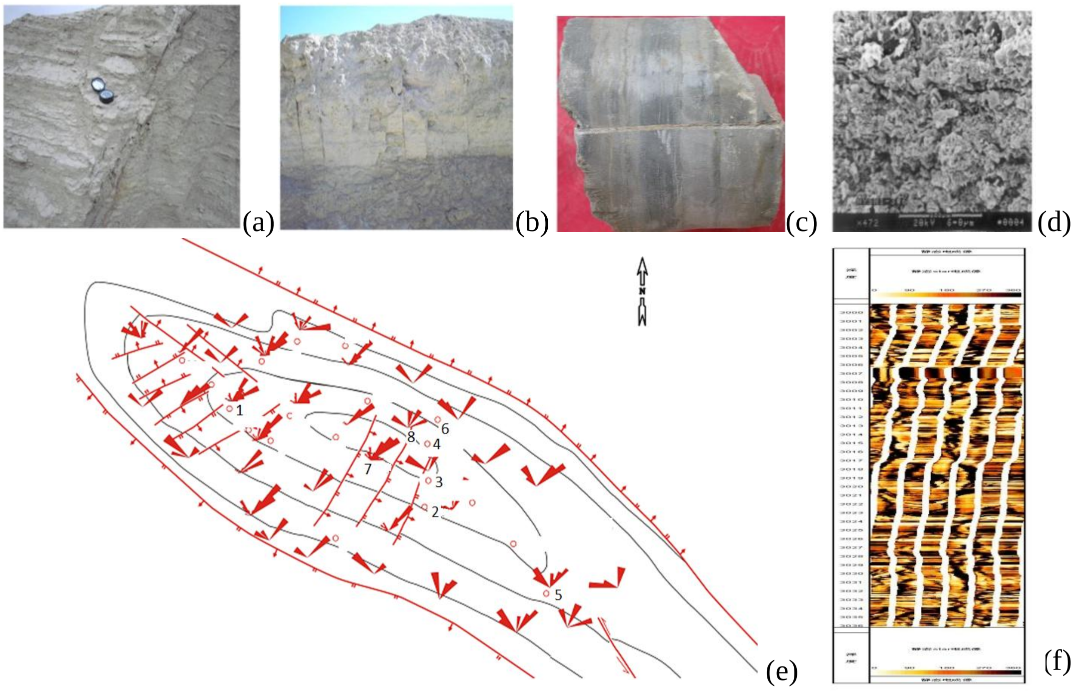


Figure 2*. (a) and (b)outcrop images show the preferred fracture orientation; (c) a core sample shows the vertical fracture in the middle; (d) micro rock slice shows small cracks among the crystals; (e) the well locations are shown in the small red circles denoted with well names. The rose diagrams show the fracture orientation distribution where the outcrops are investigated, and the red lines show the two reverse faults(two sides of the map)and other small faults; (f) the image log results from Well 1.*

Poststack P-wave seismic attributes

Careful calibration of the poststack seismic data and the logging data can enrich our knowledge of seismic data. In order to get more lateral information of geological structure and lithology, we performed a series of analysis on multiple seismic attributes, such as instantaneous frequency, max curvature, relative impedance, and so on. This analysis is combined with the calibration of well logs and synthetic seismic traces to reduce the uncertainties in the seismic section. As shown in Figure 3, the section runs from southwest to northeast across the anticline, and passes through three wells (Well 2, 3 and 4, shown in Figure 2e). The colour map in Figure 3 represents the instantaneous frequency, which is overlaid with the seismic section. The zone marked in the red closed line is the top of the reservoir which shows very strong reflection amplitude and moderate instantaneous frequency with few fractures, and it acts as a cap that preserves the gas under it. The red lines inside the yellow circles mark the fractures found at the well sections from the observed cores. The dark (green, blue and purple) zones inside the white closed line show weak reflection and low instantaneous frequency with intensive fracturing as indicated by the yellow circles. This distribution pattern of strong and weak reflection indicates the presence of the dense caprock layer at the top of the reservoir and the loose fractured rocks and the fluids in the reservoir.

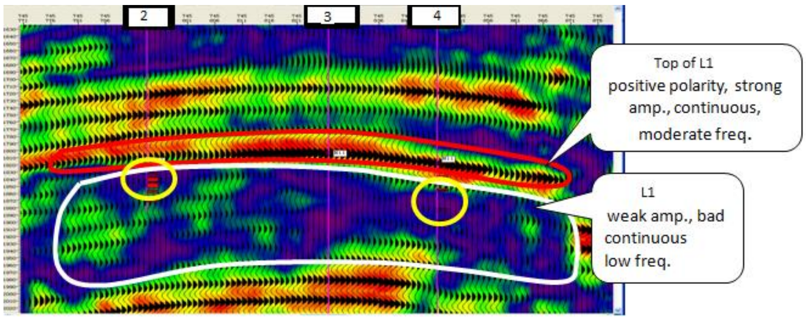


Figure 3*. Instantaneous frequency map covered with seismic section and three well logs (Well 2,3 and 4,see Figure 2e),*

Techniques for analysis of pre-stack seismic attributes

In practice, two techniques are often employed to perform azimuthal attribute analysis: full-azimuth surface fitting and narrow-azimuth stacking (Li et al. 2003; Hall and Kendall, 2003). Full azimuth surface fitting is often preferred than narrow azimuth stacking, since the latter may enhance the acquisition footprint, particularly when there is no sufficient offset coverage. In this study, the offset depth ratio is about 0.5, and we therefore choose the algorithms of full azimuth fitting.

There are quite a few factors that affect the fracture estimation with certain pre-stack seismic attributes. Among these attributes, seismic amplitude is most sensitive to seismic data quality. Therefore data processing to enhance the S/N ratio is an important step. In addition, it is also important to preserve the relative variations in the amplitude. For traveltime and interval travetime, the main factors that affect the fracture estimation is the offset/depth ratio (or offset coverage if the target depth is known) and geological structure. Sufficient offset coverage can significantly lower the influence of the geological structure. For a good estimation the offset-depth ratio should be at least 1. Otherwise, the estimation can be heavily distorted by the geological structure. .

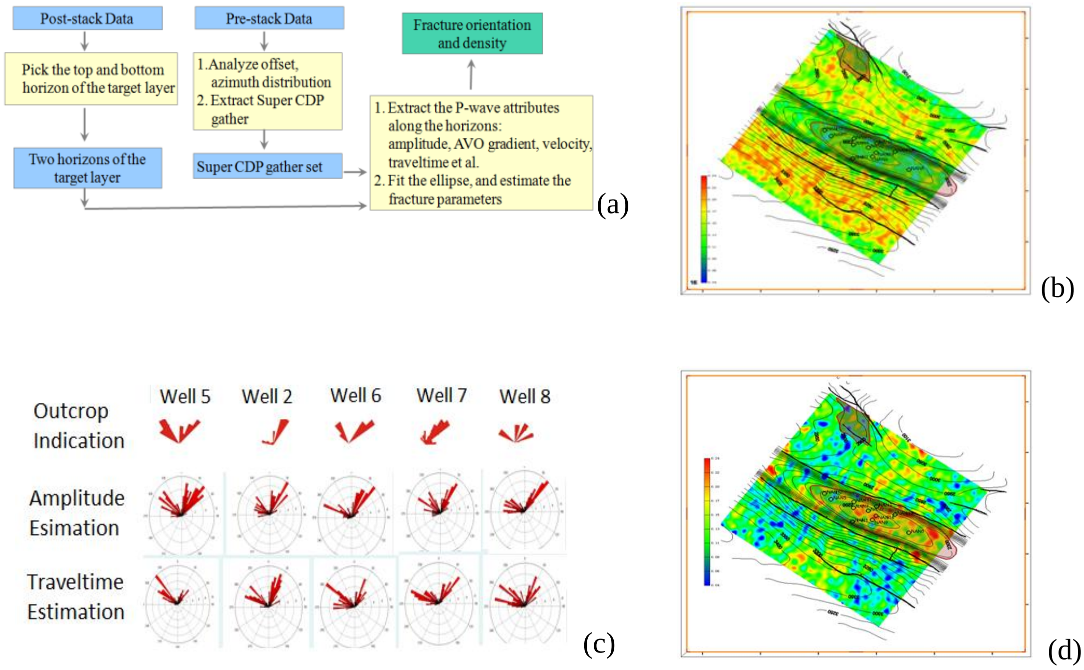


Figure 4. *(a) workflow for fracture estimation; (b) fracture density prediction using travetime attributes overlaid with the contour of the reservoir; (c) comparison of fracture orientation at the well locations obtained using different methods: outcrop and log analysis, prestack amplitude analysis and prestack traveltime analysis; (d) fracture density prediction using prestack amplitude attributes overlaid with the contour of the reservoir;*

Comparison of results

Before we perform the fracture estimation of the whole survey, we extract several super CDP gathers from the pre-stack seismic data, which are close to the cored wells. The analysis of fracture detection follows the workflow from in Figure 4a. After careful parameter testing (such as the selection of bin size, time-window size, etc.) and calibrating with the core results, we apply the optimal parameters to the whole survey. Figures 4b, 4c and 4d show the final results. As shown in Figure 4b, because of insufficient offset coverage, the fracture density estimated with the traveltime attributes are heavily influenced by the anticline structure, and we can see that the colour map is consistent with the structural contour map, and this result does not agree with the actual fracture density distribution. In contrast, as shown in Figure 4d, the fracture density estimated from the amplitude is consistent with the fracture distribution from the outcrops and the post-stack seismic attributes. However, due to the lack of good offset coverage, the acquisition footprint can still be observed along the inline direction of Figure 4d. Figure 4c compares the fracture orientation at the well locations estimated using different methods. Fracture orientation estimated using the amplitude attribute shows very good agreement with the outcrop and core results (Figure 4c).

Conclusions

We have presented an integrated study of fracture prediction using P-wave data. A comprehensive and integrated analysis has been made on the core samples, the micro rock slices, the well logs, the post-stack P-wave seismic attributes and the Pre-stack P-wave data in the study area. The results show fractures are widespread and regularly distributed in the area. Fracture estimation using Pre-stack P-wave data with the theory of azimuth anisotropy is economical and feasible in the study area. The final results estimated using azimuthal analysis of the pre-stack seismic amplitude are consistent with the results of core and log analysis at the well locations. In contrast, the results obtained from the traveltime attributes are dominant by the anticline structure due to the lack of sufficient offset coverage.

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