PS-wave Fracture Characterization Case Study: Pinedale Field, Wyoming

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Abstract

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Multicomponent 3D surveys where downgoing compressional (P) waves convert to upgoing shear (S) waves at interfaces provide a practical means for analyzing fracture properties. This is particularly important for delineating naturally fractured reservoirs by exploiting the unique characteristics of S-wave azimuthal anisotropy induced by vertical fracturing. In the presence of fractured media, S-waves split into a fast wave that is polarized parallel to fractures and a slow wave that is polarized normal to fractures. The amount of splitting (time difference between the two S-waves) is proportional to fracture intensities. To investigate this phenomenon, we utilize a wide range of source-receiver azimuths in the processing and analyze the fast and slow S-waves to extract fracture information.

A 3D three-component (one vertical and two horizontal geophones) converted-wave (PS-wave) survey from Wyoming is presented, acquired over the southern tip of the Pinedale field. The targets are naturally fractured gas sand reservoirs in the Lance formation. From the analysis of fast and slow S-waves, a regional direction of anisotropy was observed in N35W orientation. Layer-based analyses confirmed the presence of azimuthal anisotropy in the overburden, which required compensation during the processing to isolate S-wave splitting properties at reservoir depths. Results from the layer-stripping analysis suggested areas of increased fracturing in the overburden as well as at target levels that are associated with faults over the crest and along the limbs of the Pinedale anticline. Although FMI logs show mostly bedding planes near horizontal dip, at many levels where dip is larger and near vertical, the fracture strike is in agreement with the fast S-wave direction.

Introduction

Interest in the use of PS-waves to help characterize fractured reservoirs has prompted the acquisition of several multicomponent surveys around the industry. Early studies by Ata and Michelena (1995) used three 2D lines centered over a well to quantify fracture information. Although the spatial coverage was sparse, two fracture systems appeared to cause azimuthal anisotropy. A small 3D/3C survey collected in the Wind River Basin in Wyoming to calibrate a larger P-wave effort had some measure of success in characterizing fracture anisotropy (Gaiser, 1999; Grimm et al., 1999). Ocean-bottom cable surveys from the North Sea (Olofsson et al., 2002) and the Adriatic Sea (Loinger et al., 2002) showed that it was important to characterize overburden azimuthal anisotropy before deeper targets were analyzed. Furthermore, Vetri et al. (2003) showed that borehole data were in good agreement with PS-wave estimates of fracture direction at Emilio field in the Adriatic Sea.

The objective of this study was to use a PS-wave seismic survey in the Pinedale field in Wyoming to quantitatively identify naturally fractured areas in Cretaceous tight gas sand reservoirs at depths between 3,000 and 4,500 m in the Lance formation. Figure 1 shows the P-wave interpretation over the Pinedale anticline. Although these reservoirs are associated with natural fractures, they require induced fracture treatment to provide the necessary permeability for production.

Wide Azimuth Processing

A 3D/3C survey was designed and acquired to provide wide azimuth and offset coverage at the target. Receiver lines were oriented N70°E and the shot lines were oriented at 45° to the receiver lines in roughly a NW-SE orientation to yield a CMP fold of approximately 50 for P-waves and 50 for PS-waves over 25 km^2. Estimates of the principal PS-wave fast (N145E) and slow (N235) directions (denoted PS_1 and PS_2 with only one subscript) were made early in the processing to guide propagation azimuth limitations for key processing steps. These steps include surface-consistent statics and moveout velocities.

In preparation for advanced fracture analysis techniques, the data were processed in common-azimuth volumes to preserve the effects of S-wave birefringence. Both radial and transverse components were divided into eight common-azimuth sectors: 10° to 370° incrementing by 45° with a tolerance of +/-22.5°. The transverse component data were processed using the same deconvolution operators, statics, and velocities estimated from the radial component data. All volumes were then migrated using the same migration velocity field, resulting in 16 separate common-azimuth volumes of radial and transverse data. Azimuth volumes oblique to the principal directions exhibited poor fold and S/N, and so were excluded from further processing.

2Cx2C (read, 2C by 2C) Alford (1986) rotation adapted for PS-waves (Gaiser, 1999) provides a means to combine the remaining multiazimuth data into a single 2Cx2C volume. The four azimuth volumes of radial and transverse components were combined into 2Cx2C groups, rotated to the preferred PS_1 and PS_2 directions (N145°E and N235°E) and then stacked to create one set of 2Cx2C data. This four-component matrix has terms: PS_{11}, PS_{12}, PS_{21}, and PS_{22}. For each CMP, further minimization of the off-diagonal terms PS_{12}, and PS_{21} identifies the principal axes of the azimuthal anisotropy that are related to fracture orientation, and measuring the time delays between the fast, PS_{11}, and slow, PS_{22}, diagonal terms quantifies the magnitude of anisotropy related to fracture density.

Shear-wave Splitting Analysis

Before analysis of target layers, the effects of S-wave azimuthal anisotropy of the overburden must be removed. Figure 2 shows the overburden azimuthal anisotropy analysis from surface to near the base of the Fort Union. Colors represent percent anisotropy (fracture intensity), which have a peak distribution between 4% and 5%. The small lines indicate the orientation of the fast S-wave (fracture orientation), which is fairly consistent at N35˚W. Note that the more intense anisotropy occurs over the Pinedale anticline, which would be consistent with regions of more intense fracturing. Also, there appears to be a footprint from the acquisition geometry along the inline direction.

Further layer stripping below the overburden can provide azimuthal anisotropy for target layers. Production at Pinedale field is primarily from the Lance formation where fractures play an important role to assist permeability. Related to the flexure and structural complexity of the anticline are faults that cut through both fore and back limbs. Within the survey area there is a well (Antelope #15-23) on the apex of the anticline where induced fracture treatments were conduced at 9 levels over 600 m, resulting in the production of 62.7 MMcf gas and 2,123 Bbls oil over one and half years. Figure 3 shows the azimuthal anisotropy analysis over the Lance formation for near base of Lance isochron. Colors represent percent anisotropy (fracture intensity) from 1.0 to 9.5, which have a peak distribution at 4.5%. Again, note that more intense anisotropy occurs over the Pinedale anticline, but also to the east compared to the overburden. High anisotropy areas would be candidates for further investigation as potential fracture sweet spots. The principal orientation of the fast S-wave (fracture orientation) is predominantly N35˚W, but varies somewhat over the anticline.

It is important to use well log information, such as the FMI and dipole sonic logs from the Antelope 15-23 to calibrate these anisotropy results. For example, the FMI logs show mostly bedding planes near horizontal dip, but at many levels dip exceeds 30˚ and 40˚, which could be related to low-angle fracturing associated with the thrust fault tectonics at Pinedale. It is interesting that at these levels, the fracture strike is qualitatively in agreement with the principal PS-wave directions. Also, close to base of Fort Union, the strike of near vertical fractures agree with the fast S-wave orientation in Figure 2. However, for optimal calibration with the PS-wave data, the cross-dipole sonic log should be used (not available) to obtain quantitative estimates of azimuthal anisotropy orientation and magnitude. In addition, near-offset S-wave source vertical seismic profiles could be acquired. These can provide valuable S-wave splitting properties at the same seismic wavelengths as the surface data.

Conclusions

2Cx2C rotation and layer-stripping analyses of the overburden layers leads to quantifying the fracture properties at target horizons. Azimuthal anisotropy analyses over the Lance formation at the southern tip of the Pinedale anticline in the Antelope area indicate potential sweet spots of more intense fracturing. These occur along the flanks of the anticline and appear to be controlled by faulting. Although FMI logs show mostly bedding planes near horizontal dip, at many levels where dip is larger and near vertical, the fracture strike is in agreement with the fast S-wave direction.

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References

Alford, R.M., 1986, Shear data in the presence of azimuthal anisotropy: Dilley, Texas: 56th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 476-479.

Ata, E., and Michelena, R.J., 1995, Mapping distribution of fractures in a reservoir with P-S converted waves: *The Leading Edge*, **14**, 664-676.

Gaiser, J.E., 1999, Applications for vector coordinate systems of 3-D converted-wave data: *The Leading Edge*, **18**, 1290-1300.

Grimm, R.E., Lynn, H.B., Bates, C.R., Phillips, D.R., Simon, K.M., and Beckham, W.E., 1999, Detection and analysis of naturally fractured gas reservoirs: multiazimuth seismic surveys in the Wind River Basin, Wyoming: *Geophysics*, **64**, 1277-1292.

Loinger, E., Gaiser, J.E., Lucini, A., Prestoni, M., and Walters, R.M., 2002, 3D/4C Emilio: Azimuth processing for anisotropy analysis: 64th Ann. Internat. Mtg., Eur. Assn. Geosci. Eng., Extended Abstracts, F-23.

Olofsson, B., Kommedal, J., Barkved, O., Alexandre, R., Brunelliere, J., and Muyzert, E., 2002, Continuous progress in processing multicomponent data – A case study: 64th Ann. Internat. Mtg., Eur. Assn. Geosci. Eng., Extended Abstracts, F-22.

Vetri, L., Loinger, E., Gaiser, J., Grandi, A. and Lynn, H. 2003, 3D/4C Emilio: Azimuth processing and anisotropy analysis in a fractured carbonate reservoir: *The Leading Edge*, **22**, 675-679.

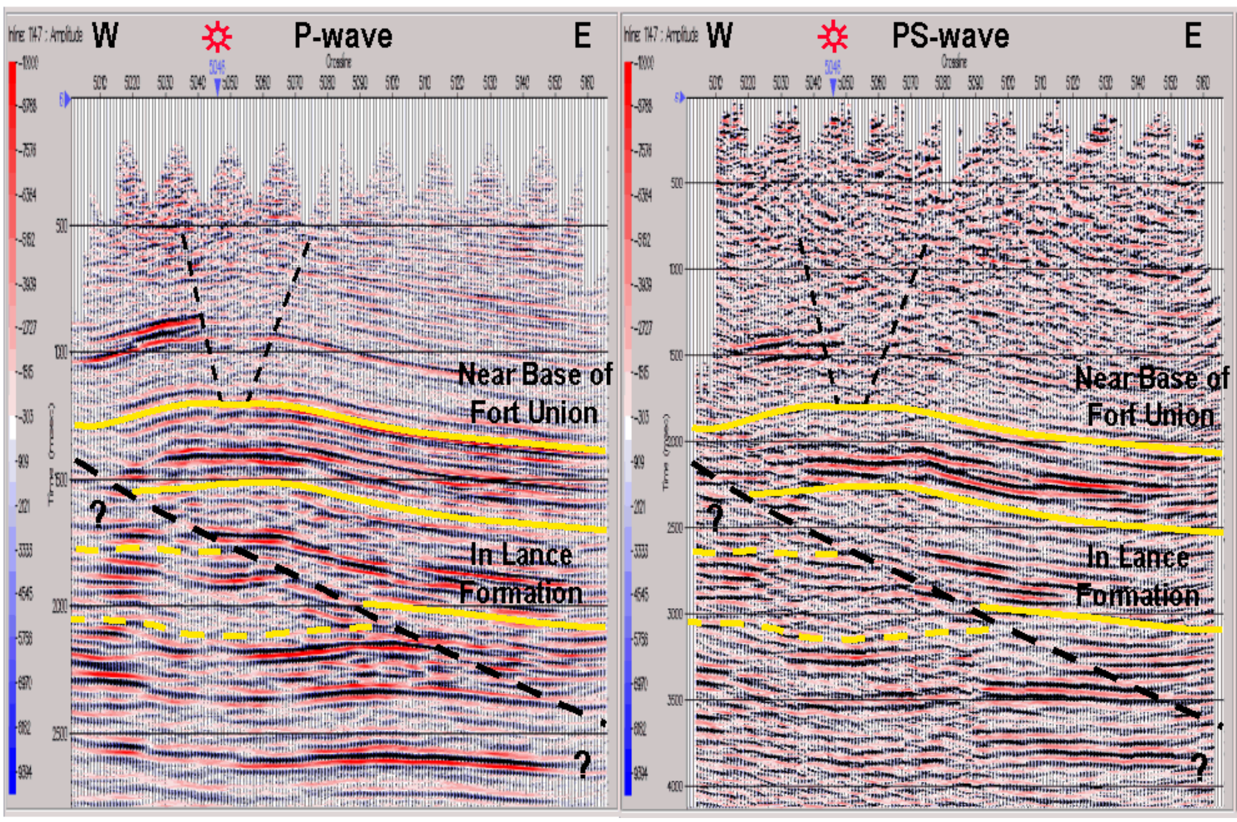

Figure 1. P-wave interpretation over the Pinedale anticline where production occurs in Cretaceous tight gas sands in the Lance formation. Note that the PS-wave section, compressed in time compared to the P-wave by a Vp/Vs factor of two, agrees very well with the P-wave interpretation.

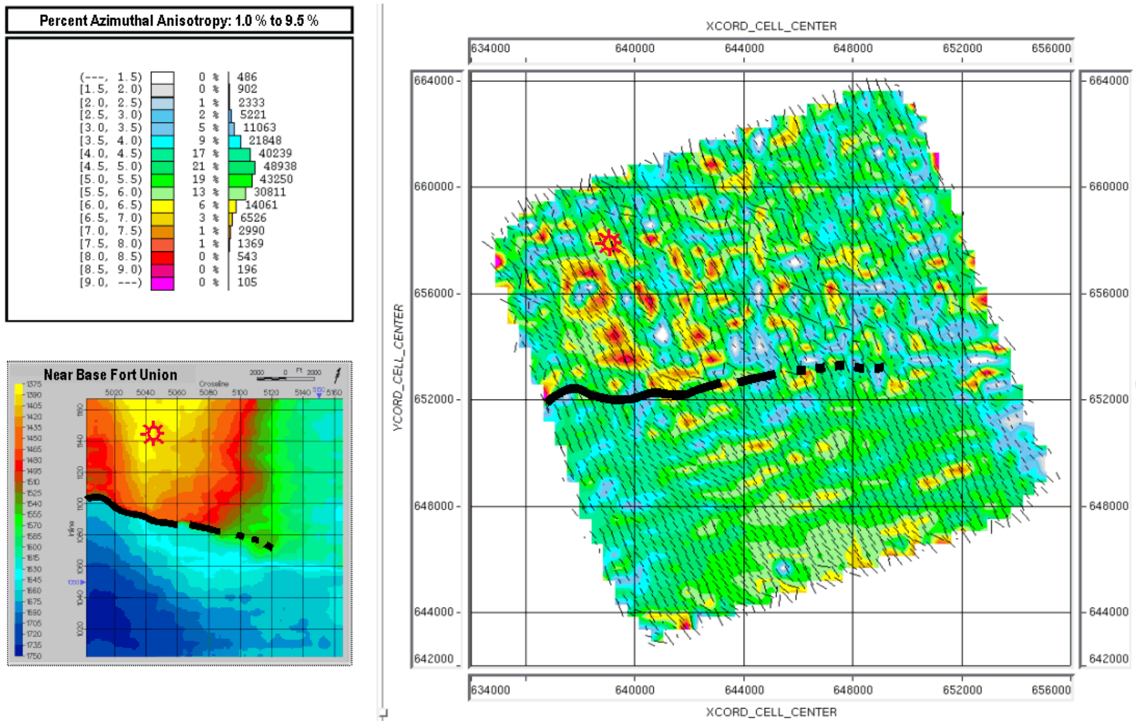

Figure 2. Anisotropy analysis (right) from surface to near base of Fort Union isochron (left). Colors represent percent anisotropy (fracture intensity) from 1.0 to 9.5, which have a peak distribution at 4.5%. The small lines indicate the orientation of the fast S-wave (fracture orientation), which averages N35˚W. At the Antelope 15-23 well, N20˚W fast S-waves agree with the strike of near vertical fractures seen on the FMI log close to base of Fort Union. Note that the more intense anisotropy occurs over the Pinedale anticline, which would be consistent with regions of more intense fracturing.

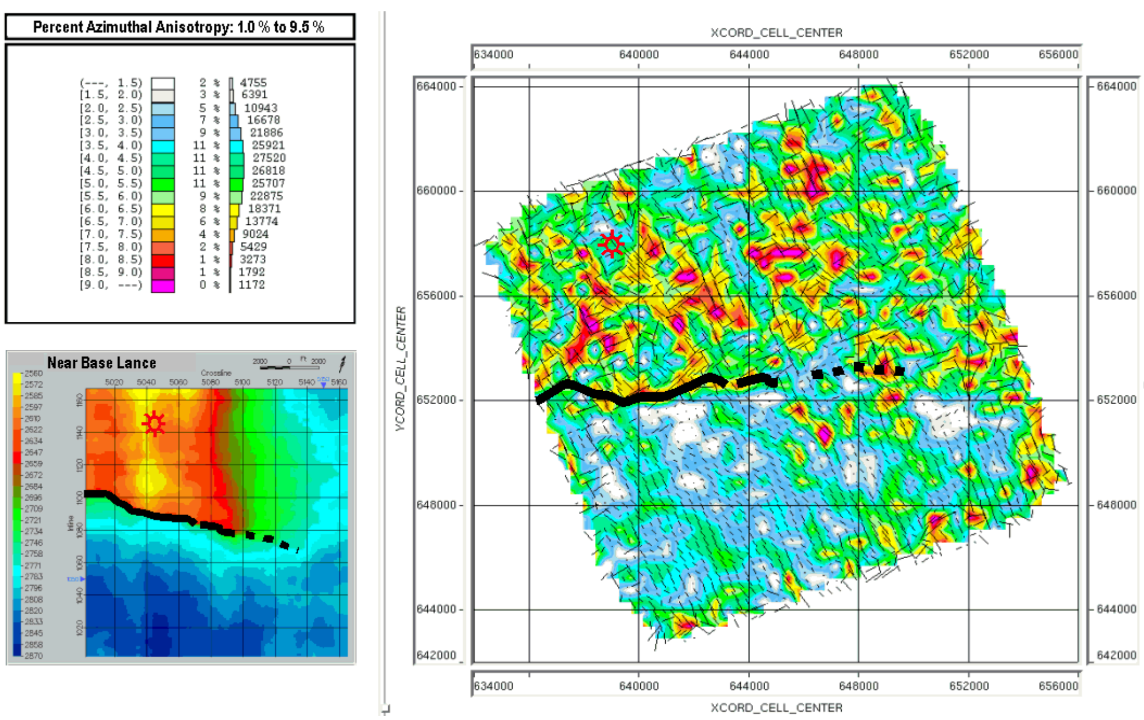

Figure 3. Azimuthal anisotropy analysis (right) over the target for near base of Lance isochron (left). Colors represent percent anisotropy (fracture intensity) from 1.0 to 9.5, which have a peak distribution at 4.5%. Again, note that more intense anisotropy occurs over the Pinedale anticline, but there are also high anisotropy areas further to the east.