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Multicomponent Processing and Fracture Characterization Analysis at Pinedale Field and Washakie Basin, Wyoming

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Abstract

Multicomponent 3-D 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.

Two 3-D 3-component (one vertical and two horizontal geophones) surveys from Wyoming are presented: one acquired over the southern tip of the Pinedale Field in the Antelope area and the other in the Washakie Basin. The targets are naturally fractured gas sand reservoirs. From the analysis of fast and slow S-waves the same regional direction of anisotropy was observed in both areas. Layer-based analyses measured anisotropy in the overburden, which required compensation during the processing to isolate the variations at reservoir depths. Eight limited-azimuth volumes were created for the two horizontal geophone components. These volumes were analyzed to determine the time-variant anisotropy within the surveys and indicated areas of increased fracturing in the overburden as well as at target levels.

Introduction

Recent interest in the use of PS-waves to help characterize fractured reservoirs has prompted the acquisition of several multicomponent surveys around the industry. Ata and Michelena (1995) used three 2-D lines centered over a well to quantify fracture information. Although the spatial coverage was sparse, azimuthal anisotropy appeared to be caused by two fracture systems. A small 3-D/3-C 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; and Grimm *et al*., 1999). Ocean bottom cable surveys from the North Sea (Olofsson et al., 2002) and Adriatic Sea (Loinger et al., 2002) showed that it was important to characterize overburden azimuthal anisotropy before deeper targets were analyzed.

The objective of these studies was to use a PS-wave seismic survey in the Pinedale field and Washakie Basin in Wyoming to quantitatively identify fractured areas in a naturally fractured Cretaceous sandstone reservoir at depths between 3,000 and 4,500 m. 3-D/3-C surveys were designed and acquired to provide wide azimuth and offset coverage at the target. In the Pinedale survey, receiver lines were oriented N70E and the shot lines were oriented at 45 degrees to the receiver lines in a NW-SE orientation to yield a CMP fold of approximately 50 (P-wave) and 50 (PS-wave) over 25 sq km. At Washakie Basin the receiver lines were oriented E-W and a diagonal brick shot pattern was acquired to yield a CMP fold of approximately 98 (P-wave) and 98 (PS-wave) over 50 sq km. A detailed processing methodology was developed to preserve the effects of S-wave birefringence and prepare the data volume for further fracture analysis. 2Cx2C (read, 2C by 2C) Alford (1986) rotation adapted for PS-waves (Gaiser, 1999) provided a means to combine the multi-azimuth data into a single 2Cx2C volume. This 4-component matrix has terms: PS_{11}, PS_{12}, PS_{21}, and PS_{22}.

Data processing

Estimates of the principal PS-wave fast and slow directions (denoted PS_1 and PS_2 with only one subscript) are made early in the processing to guide propagation azimuth limitations for key processing steps. These include surface-consistent statics and moveout velocities. In preparation for advanced fracture analysis techniques, the data are processed in common-azimuth volumes and then all azimuths are combined using 2Cx2C rotation into a single group after azimuthal residual statics.

Processing of the vertical component, P-wave data proceeded using conventional time processing techniques. Initial processing of the horizontal data included rotation to the radial and transverse components in a source-centered coordinate system (Gaiser, 1999), geometric spreading corrections, surface-consistent deconvolution, and time-variant spectral whitening. Source statics computed from the P-wave processing were also applied to the PS-wave data, as well as elevation corrections at the receivers. Preliminary stacking velocities were estimated and an initial common-conversion point (CCP) binning correction was applied to the data. Five passes of residual receiver statics were computed while iterating with additional passes of velocity analysis and anisotropic, depth-dependent CCP binning.

Key locations within the surveys were identified for analysis of preferred PS-wave polarization directions. At each location, a large azimuth supergather measuring 536 by 670 m (17 x 21 CCP gathers) was extracted and sorted into limited azimuth gathers. All statics were applied and the data were NMO corrected, muted, and stacked. This was done for both the radial and transverse components and resulted in azimuthal stack traces every 10 degrees (Figure 1). The transverse component showed clear polarity reversals every 90 degrees and the radial component demonstrated a variation in traveltime with azimuth. Based on these results, the fast PS_1 direction was determined to be approximately N135°E and the slow PS_2 direction, N225°E for both surveys.

The results of the supergather analysis also suggested that, by limiting the radial component data to the principal directions, better quality PS-wave reflections could be obtained. The data volume was limited to the PS_1 and PS_2 propagation directions (+/-22.5°), stacked and migrated. Additional residual receiver-static corrections were then computed using these limited azimuth volumes and improved stacks. While these PS_1 and PS_2 volumes proved to be better quality than the all-azimuth product, additional propagation directions, and the transverse data needed to be incorporated into the final results.

In preparation for subsequent fracture detection analysis, the entire data volume, both radial and transverse components, was divided into eight common-azimuth sectors: 0° to 360° incrementing by 45° with a tolerance of +/-22.5°. The transverse component data was 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. This resulted in 16 separate common-azimuth volumes of radial and transverse data (Figure 2). These components exhibited azimuthally varying traveltimes and, to combine them into a single dataset for improved fold and enhanced signal, 2Cx2C rotations were applied. Each 2Cx2C set was rotated into the preferred fast (PS_{11}) and slow (PS_{22}) directions (N135°E and N225°E) and stacked to create one set of 2Cx2C data for further analysis. Again, this increased the fold and resulted in improved signal quality when compared to the initial azimuth-limited stack.

However, small residual time shifts between PS_{11} and PS_{22} were observed in the data for each of the eight common-azimuth directions and components. To correct for this and improve the combined stack, azimuth-consistent static corrections were computed to align the radial component data in both the PS_{11} and PS_{22} propagation directions. After applying these corrections to the radial and respective transverse components for each azimuth direction the resulting stacks were significantly improved.

Birefringence analysis

One of the most important steps in using PS-waves for fracture detection is to quantify the overburden azimuthal anisotropic properties and remove these S-wave splitting effects. These properties include the orientation of the principal S-wave directions, used to identify fast and slow waves for processing, and the differential velocity between the fast and slow waves. Using azimuth supergathers from preprocessing analyses or CDP-migrated data, these properties can be determined from 2Cx2C Alford (1986) rotation and Winterstein and Meadows (1991) layer-stripping methods.

Another important property of the overburden is the time variation of azimuthal anisotropy. One approach to estimate this S-wave azimuthal anisotropy in the overburden is to analyze PS_{11} and PS_{22} velocity ratios (Gaiser, 1996) as a function of two-way time. Figure 3 shows an analysis between the fast and slow data located in the northern part of the Washakie Basin survey. The vertical axis is PS_{11} two-way time and the horizontal axis is the ratio of Vps_{11}/Vps_{22} average velocity. Variable density (color) represents positive cross-correlation coefficients between the two waves. Depending on the velocity ratio, PS_{22} is stretched (< 1.0) or compressed (> 1.0), and then correlated with the PS_{11} at predefined window times. Contours superimposed on the plot indicate constant time delays of PS_{22} in milliseconds.

A maximum correlation trend can be clearly interpreted and is indicated by the dashed line. This corresponds to the time-variant velocity ratio of Vps_{11}/Vps_{22}. Above 1.0 s the trend is unknown. However, below 1.0 s the trend increases to a maximum of 30 ms at about 1.3 s and then roughly follows the 30 ms PS_{22} time delay until about 2.5 s. In the absence of the upper 1.0 s of data, the base of the shallow overburden can be interpreted at about 1.5s. It represents an interval of relatively homogeneous, azimuthally anisotropic material with constant orientation confirmed by azimuth-supergather analyses. Notice that the trend increases to almost the 40 ms PS_{22} time delay contour at about 2.5 s, and then to over 40 ms around 5.0 s, indicating increases in S-wave splitting with time.

Before analysis of target layers the effects of S-wave azimuthal anisotropy of the overburden must be removed. Figures 4 and 5 show the overburden azimuthal anisotropy analysis from surface to near the base of the Fort Union at Washakie basin and the Pinedale field, respectively. Colors represent percent anisotropy (fracture intensity), which have a peak distribution between 3% and 4%. The small lines indicate the orientation of the fast S-wave (fracture orientation), which is fairly constant at N45˚W for both surveys. Note that the more intense anisotropy occurs along the flanks of the Pinedale anticline, which is consistent with regions of extensional fracturing. Also there is a faint continuation of the more intense anisotropy south of the east-west fault. It is interesting that at Washakie basin the more intense anisotropy occurs along lineaments observed in the P-wave data.

Further layer stripping below the overburden can provide azimuthal anisotropy for target layers. It is important to remember that the property we are analyzing for fracture detection is the transmission effect on S-waves: the birefringence orientation and the time separation. Off-diagonal components are minimized further by 2Cx2C rotations to estimate any change in the direction of the principal axes. After minimization, the separated PS_{11} and PS_{22} waves are correlated and PS_{22} is aligned with PS_{11}. These properties can then be interpreted as lateral variations in fracture orientation and intensity.

Production along the Pinedale anticline is primarily from the Lance where fracturing can play an important role owing to the flexure and structural complexity. There are also thrust faults that cut through both fore and back limbs of the anticline. Figure 6 shows the azimuthal anisotropy analysis over part of the Lance Formation for near base of Lance isochron. Colors represent percent anisotropy (fracture intensity) from 0.0 to 10.5, which have a peak distribution of 5%. Note that more intense anisotropy occurs along the flanks of the Pinedale anticline and the east-west fault, but has shifted somewhat to the east compared to the overburden. These areas are candidates for further investigation as potential fracture sweet spots. The principal orientation of the fast S-wave (fracture orientation) is predominantly N45˚W. It is important to use well log information to calibrate these anisotropy results.

Conclusions

Early estimation of the principal S-wave orientation is critical to optimize processing for fracture characterization. This can be accomplished using azimuth supergather analyses at selected locations. Once these directions are determined, propagation azimuths may be limited to improve signal quality for various data processing steps. Rotating the data to the fast and slow PS-wave directions can improve surface consistent static corrections and velocities. Rotating back to radial and transverse and processing common-azimuth volumes allowed all the data to be combined using 2Cx2C Alford rotation. This increased fold helped improve the signal quality, but only after azimuth-consistent static corrections were computed and applied.

Vps_{11}/Vps_{22} (fast shear to slow shear) velocity ratio analysis is a valuable tool to quantify the time variant nature of S-wave birefringence. This ratio indicates different layers in the subsurface where birefringent properties may have changed. One of the most important of these layers is the overburden, which can be removed effectively by 2Cx2C rotation and layer-stripping analyses, and leads to quantifying the fracture properties at target horizons. Azimuthal anisotropy analyses 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. Similar association of azimuthal anisotropy with structural features (faults and lineaments) is also observed in the Washakie Basin.

Acknowledgments

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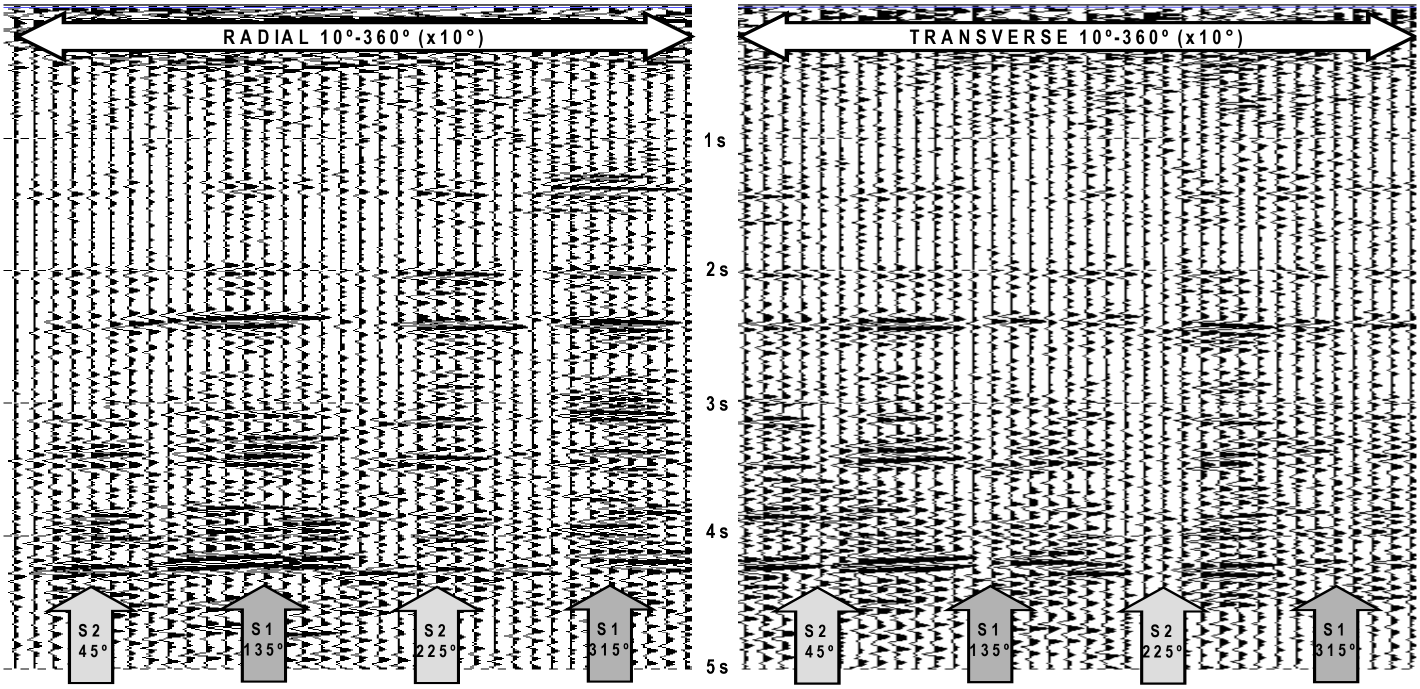

Figure 1. Azimuth-gather stacks from the Washakie Basin survey of the radial (left) and transverse (right) component at 10-degree increments from 10 to 360 degrees. The transverse components show significant interference between the fast and slow S-wave, and polarity reversals every 90 degrees indicate the azimuths of the natural-coordinate frame where S-wave splitting is minimal. The radial component shows that the fast S-wave polarization direction is aligned with N137°E and N317°E degrees, and that the slow S-wave direction is aligned with N47°E and N227°E degrees. At intermediate azimuths between the fast and slow directions there is significant interference that results in low amplitudes on the radial component. Clearly an all azimuth stack would be very poor.

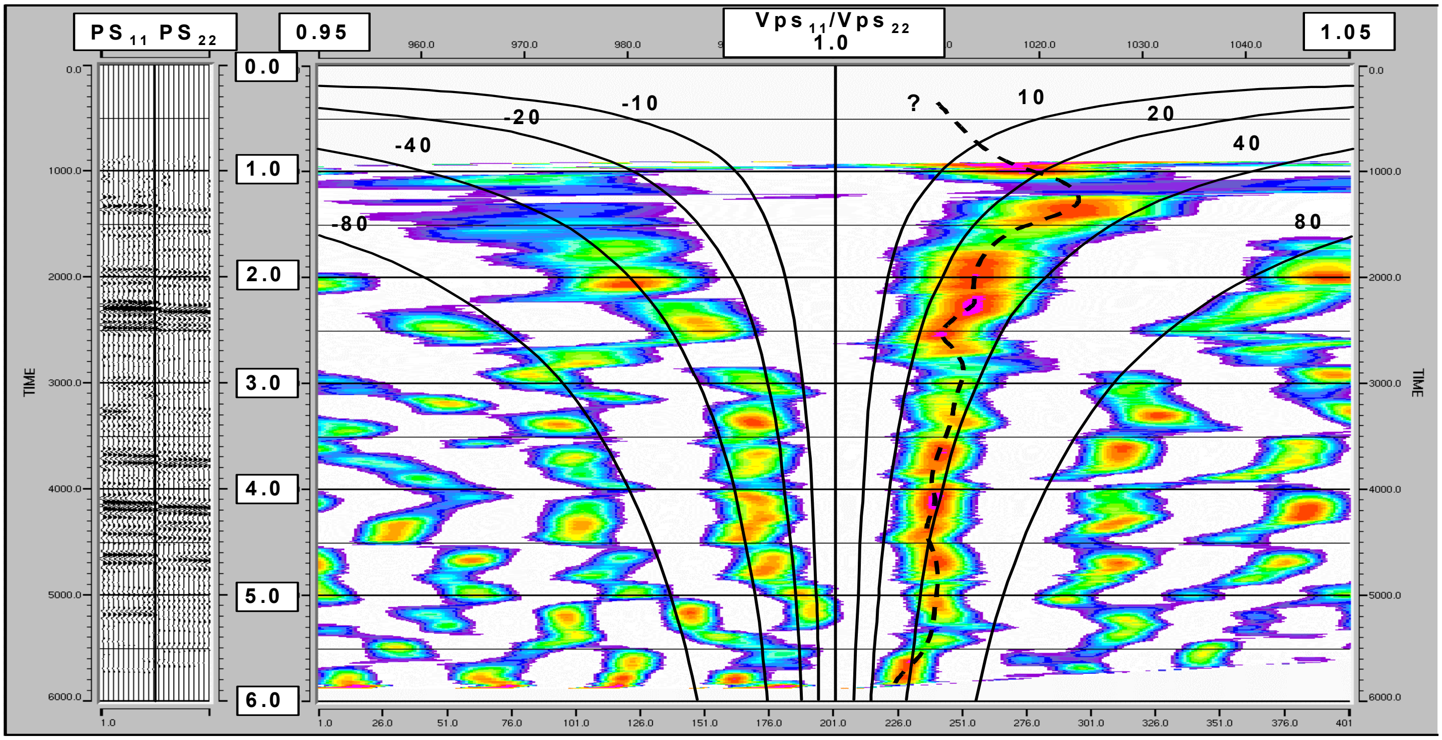

Figure 3. Average velocity ratio analysis between the PS_{11} and PS_{22}.traces (left) in the northern part of the Washakie Basin survey. The Vps_{11}/Vps_{22} average velocity ratio ranges from 0.95 to 1.05, time is two-way PS_{11}, and variable density (color) represents positive cross-correlation coefficient values between 0 and 1 (magenta). Black contours indicate constant PS_{22} time delays (ms) and the dashed line shows the interpreted relationship between the split S-waves. The base of the shallow overburden for this study is interpreted where the traveltime difference increases to about 30 ms at 1.3 s.

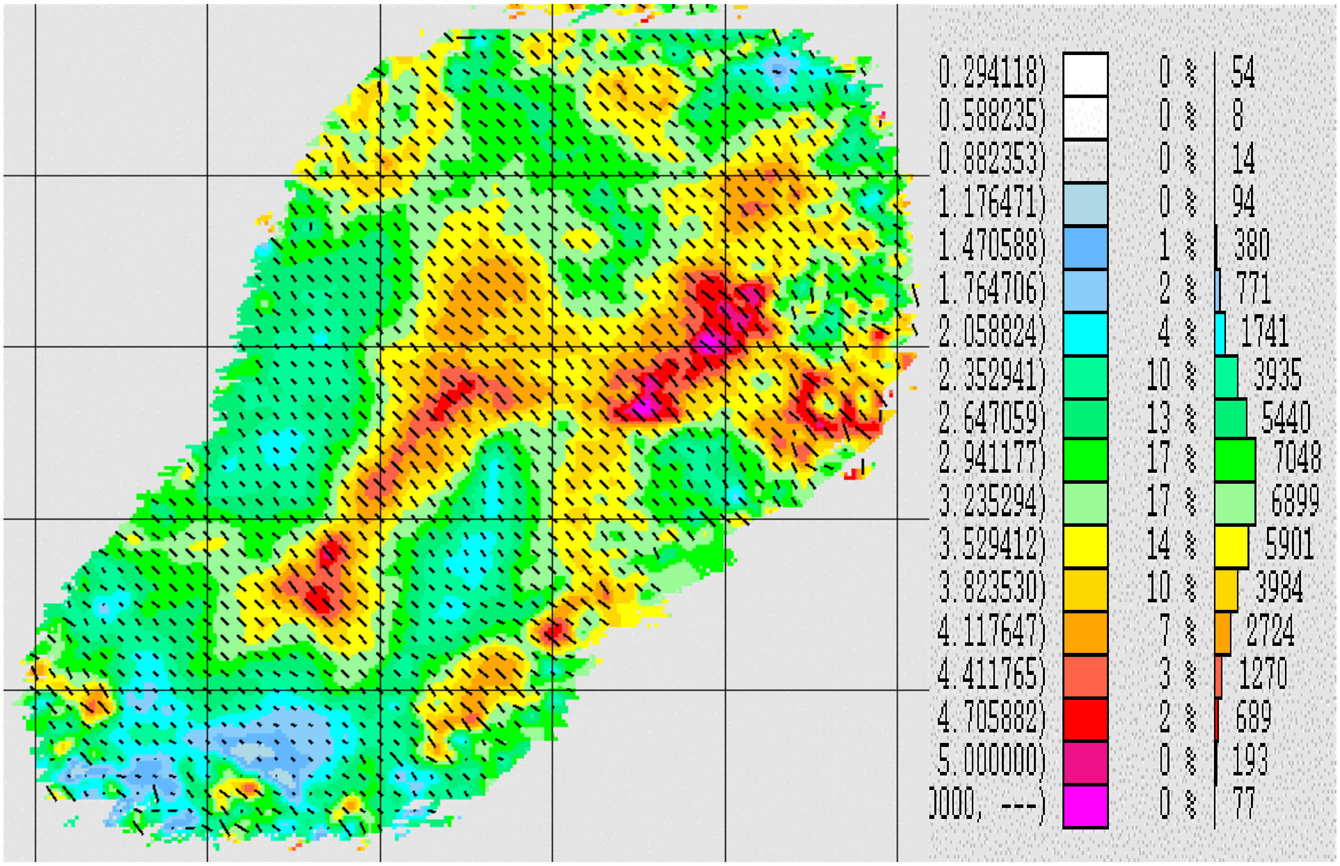

Figure 4. Map view of the percent anisotropy in color of the overburden. Percent anisotropy ranges from 0 to 5, and the peak distribution is just at 3%. Notice the northern location has about 2.5% and is less than the southern location at about 4%. High anisotropy trends in the overburden possibly indicate areas of more intense fracturing. There is an interesting linear trend in the southwest corner. Small vectors show the orientation of the fast S-wave direction, where their length and boldness are proportional to the percent anisotropy. Orientations are essentially constant everywhere.

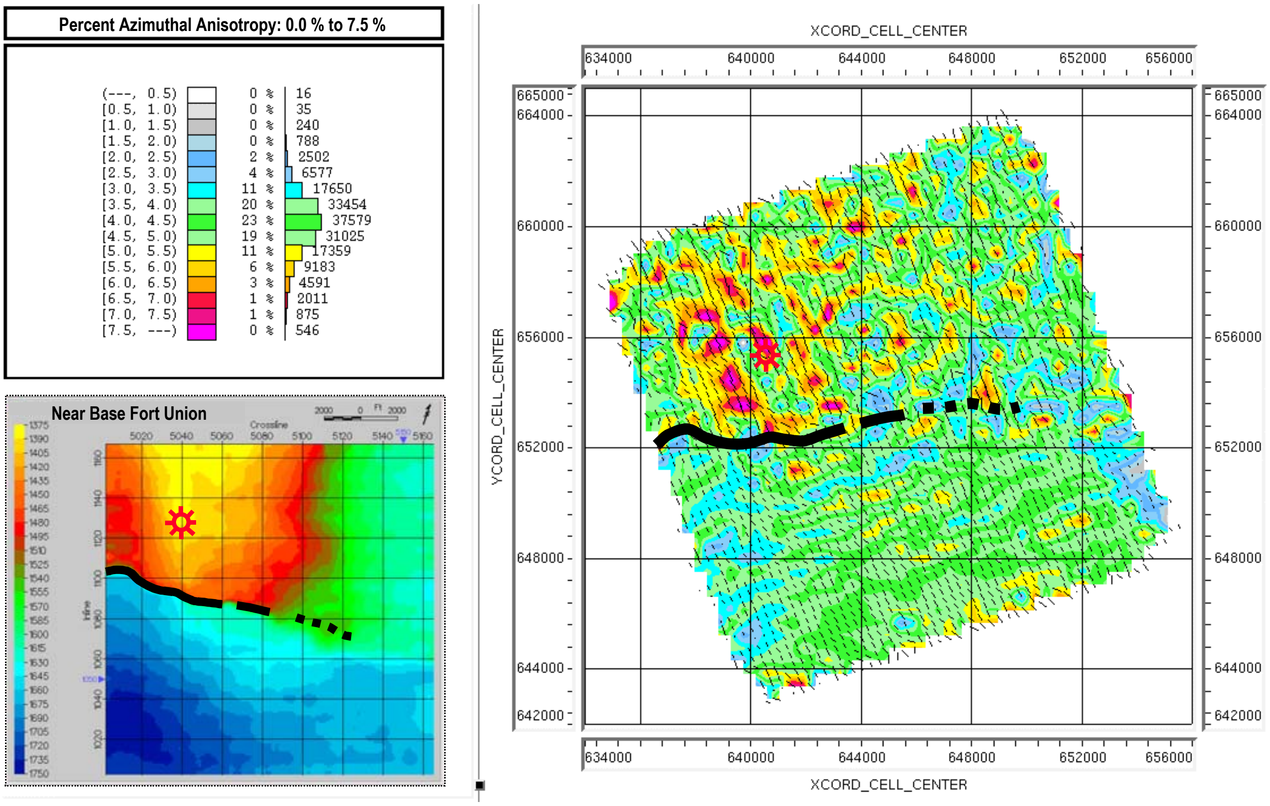

Figure 5. This shows the anisotropy analysis (right) from surface to near base of Fort Union isochron (left). Colors represent percent anisotropy (fracture intensity) from 0.0 to 7.5, which have a peak distribution at 4%. The small lines indicate the orientation of the fast S-wave (fracture orientation), which is fairly constant at N45˚W. Note that the more intense anisotropy occurs along the flanks of the Pinedale anticline, which is consistent with regions of extensional fracturing. Also there is a faint continuation of the more intense anisotropy south of the fault. There is a noticeable footprint from the acquisition geometry.

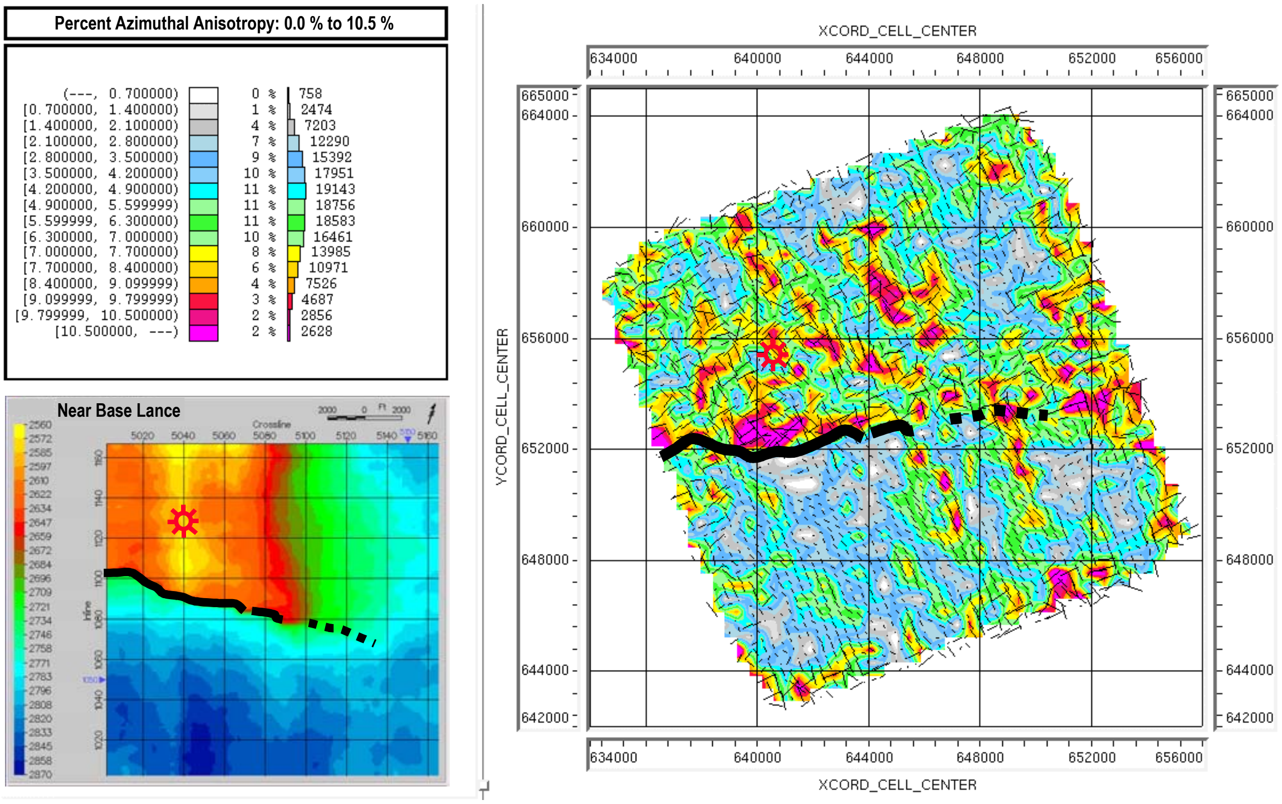

Figure 6. This shows the azimuthal anisotropy analysis (right) over the target for near base of Lance isochron (left). Colors represent percent anisotropy (fracture intensity) from 0.0 to 10.5, which have a peak distribution of 5%. Note that more intense anisotropy occurs along the flanks of the Pinedale anticline and the east-west fault, but has shifted somewhat to the east. The principal orientation of the fast S-wave (fracture orientation) is predominantly N45˚W.