Processing PS-Wave Data from A 3-D/3-C Land Survey for Fracture Characterization

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Summary
The investigation of S-wave birefringence (splitting) using 3-D converted P to S-waves (PS-waves) is an important tool for characterizing reservoir fractures. In azimuthally anisotropic media, fracture intensities are directly related to traveltime differences between the fast and slow S-waves. Fracture orientations can also be determined from the polarization direction of the fast S-wave. These effects are accurately analyzed in a 3-D/3-C survey from the Green River basin in Wyoming to preserve meaningful azimuthal variations in amplitudes and traveltimes. Estimates of the principal PS-wave fast and slow directions (PS_1 and PS_2) are made early in the processing to guide propagation azimuth limitations on the data for key processing steps including, surface-consistent deconvolution, statics, and moveout velocities. In preparation for advanced fracture analysis techniques, the data is processed in common-azimuth volumes and then all azimuths are combined using 2Cx2C Alford rotation into a single group.

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). In 2000, the first marine 3-D/3-C survey was acquired at the Emilio field in the Adriatic for the purpose of characterizing fracture porosity (Gaiser *et al.*, 2001).

The objective of this study was to use a PS-wave seismic survey in the Green River basin in Wyoming to quantitatively identify fractured areas in a naturally fractured Cretaceous sandstone reservoir at depths between 3,000 and 4,500 m. A 3-D/3-C survey was designed and acquired to provide wide azimuth and offset coverage at the target. The receiver lines were oriented N-S/E-W and a diagonal brick shot pattern was acquired to yield a CMP fold of approximately 24 over 50 km^2. A detailed processing methodology was developed to preserve the effects of S-wave birefringence and prepare the data volume for further fracture analysis.

Preliminary Processing
Processing of the vertical component, P-wave data proceeded using conventional time processing techniques. This included refraction statics analysis, residual statics, geometric spreading corrections, surface-consistent deconvolution, model-based phase correction, DMO, and poststack time migration. 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.

Supergather Analysis
Two key well locations within the survey were identified for further analysis of preferred PS-wave directions. At each of these locations, a large azimuth supergather measuring 536 by 670 m (17 x 21 CCP gathers) was extracted, centered on the well. These data were then 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 the azimuth gather stack traces shown in 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. This was consistent at both well locations.

Azimuth Limited Processing
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. Figure 2 shows a comparison with the initial all-azimuth stack. Additional residual receiver-static corrections were then computed using these limited azimuth volumes and improved stacks. Separate PS_1 and PS_2 static corrections were estimated as well as a combined decomposition of PS_1 and PS_2 together. The combined surface-consistent decomposition proved to be as good or better than the individual PS_1 and PS_2 estimates and was considered to be the more conservative approach that did not introduce additional traveltime variations between the fast and slow volumes.

Conventional stacking velocity analyses were also evaluated for both PS_1 and PS_2 directions, but no significant differences were observed. Ideally, surface-consistent deconvolution operators should also be derived for each principal direction. Previous tests, however, showed that the non-stationary effect of S-wave splitting, combined with large analysis windows, help minimize any deleterious effects that may result in combining the two directions into radial and transverse components.

While the previously described PS_1 and PS_2 volumes proved to be better quality than the all-azimuth product originally created, all the data was not being used. Additional propagation directions, previously excluded, needed to be incorporated into the results. The transverse data also needed to be processed and included in the evaluation.

Data Processing for 4-C Rotation and Layer Stripping

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. To combine these radial and transverse components with azimuthally varying traveltimes into a single dataset for improved fold and enhanced signal, 2Cx2C Alford (1986) rotations were applied to the eight common-azimuth volumes. Each 2Cx2C set was rotated into the preferred PS_1 and PS_2 directions (N135°E and N225°E). Once oriented in a common direction, they could then be stacked to create one set of 2C x 2C 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_1 and PS_2 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_1 and PS_2 propagation directions. These corrections were also applied to the respective transverse components for each azimuth direction. In contrast to conventional residual statics, a less conservative approach was taken because of the significant improvements in the PS_1 and PS_2 stacks. In addition, residual shifts introduced to PS_1 and PS_2 will tend to be removed during the overburden layer stripping process (Winterstein and Meadows, 1991), and should not affect estimates of birefringence at the reservoir level. With the data better aligned, the resulting stack was again improved (Fig. 3) compared to the uncorrected stack, and ready for detailed fracture analysis (Gaiser and Van Dok, 2001).

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 to the fast and slow PS-wave directions can improve surface consistent deconvolution, 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 Alford rotation and used in subsequent analyses. This increased fold helped improve the signal quality, but only after azimuth-consistent static corrections were computed and applied.

Acknowledgments

We thank Jonathan Fried at WesternGeco for his help in processing the converted-wave data for this study. Thanks also to EOG Resources, Tom Brown Inc., and Basin Exploration for their participation and for providing valuable insights into the nature of the reservoir.

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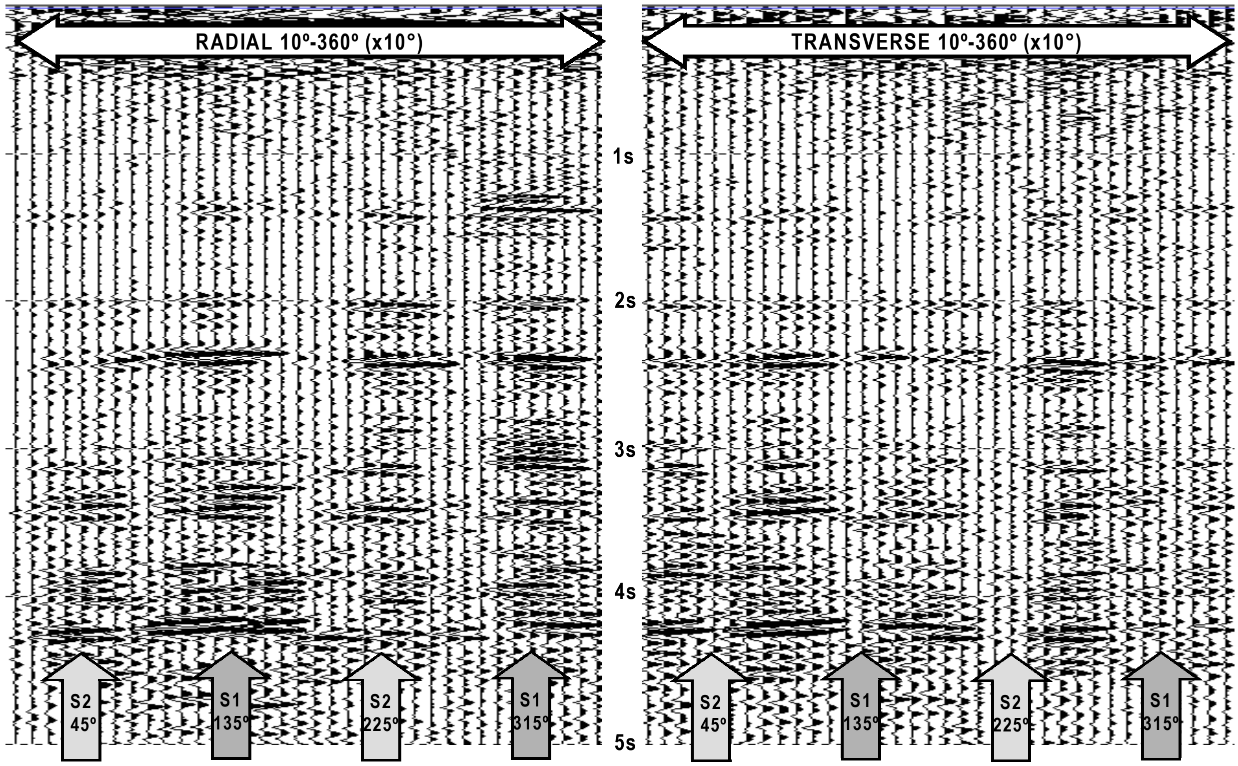
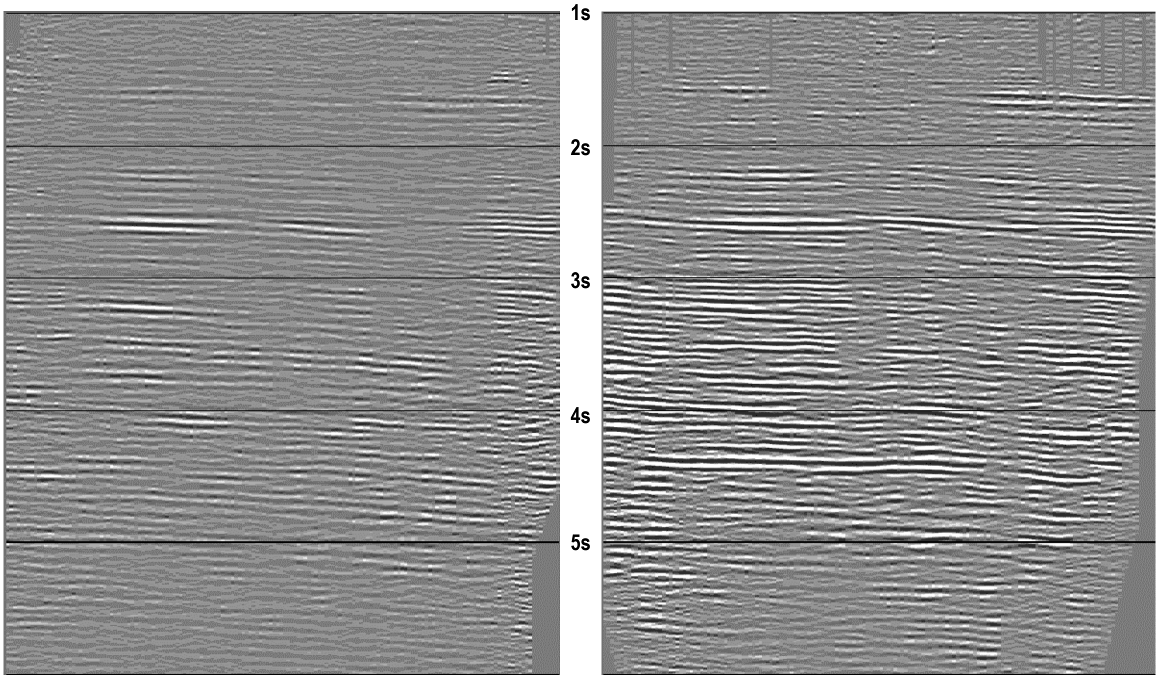
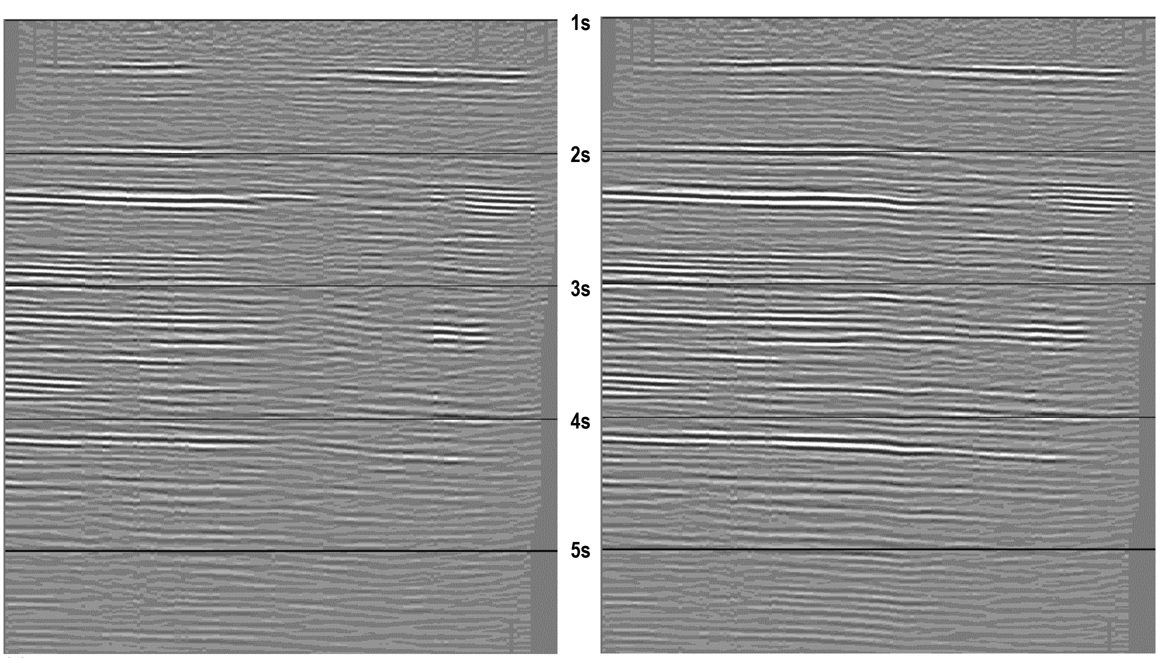


Figure 1. Azimuth-gather stacks of the radial (left) and transverse (right) component at 10-degree increments from 10 to 360 degrees. The transverse components show significant interference between the fast and slow S-wave and polarity reversals every 90 degrees indicate the azimuths of the natural-coordinate frame. The fast S-wave polarization direction is aligned with N135°E degrees and the slow S-wave direction is aligned with N225°E degrees.



(a) (b)

Figure 2. (a) All-azimuth stack of the radial component versus (b) PS_1 azimuth-limited stack. Although reduced in fold, the PS_1 azimuth-limited stack shows better reflection continuity and stronger signal strength.



(a) (b)

Figure 3. (a) Radial component stack of eight combined propagation azimuths after rotation to the principal PS_1 direction (N137°E). (b) Same stack with azimuth-consistent static corrections applied showing improved reflector continuity, particularly on the right half of the line.