PROCESSING AND ANALYSIS OF PS-WAVE DATA FROM A 3-D/3-C LAND SURVEY FOR FRACTURE CHARACTERIZATION

R. VAN DOK, J. GAISER, and J. MARKERT

WesternGeco., 1625 Broadway, Suite 1300, Denver, Colorado, 80202, USA

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 and fracture orientations are related to 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 variation in amplitude and traveltime. 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 during processing. In preparation for advanced fracture analysis techniques, the data are processed in common-azimuth volumes and all azimuths are combined using 2Cx2C Alford rotation into a single group after azimuthal residual statics. Ratios of PS_1 and PS_2 average vertical velocity are particularly important to identify the vertical extent of overburden anisotropy, as well as reservoir horizons. Overburden effects can be removed by 2Cx2C rotation and layer-stripping analyses before characterizing deeper horizons. In addition, less quantitative attributes such as residual off-diagonal 2Cx2C amplitudes and isochron differences between PS_1 and PS_2 are shown.

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 E-W and a diagonal brick shot pattern was acquired to yield a CMP fold of approximately 24 over 50 km^2.

Data Processing

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.

At two key well locations, a large azimuth supergather measuring 536 by 670 m (17 x 21 CCP gathers) was extracted, consisting of radial and transverse component azimuthal stack traces every 10 degrees. The transverse component showed clear polarity reversals every 90 degrees and the radial component demonstrated a variation in traveltime with azimuth. The fast PS_1 direction was approximately N135E and the slow PS_2 direction N225E at both well locations. 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 computed using these limited azimuth volumes and improved stacks.

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 deg, incrementing by 45 deg with a tolerance of +/-22.5 deg. The transverse component data was processed using the same deconvolution operators, statics, and velocities estimated from the radial component data. All volumes were migrated using the same migration velocity field. This resulted in 16 separate common-azimuth volumes of radial and transverse data. These components exhibited azimuthally varying traveltimes and to combine them into a single dataset for improved fold and enhanced signal, 2Cx2C Alford (1986) rotations, adapted for PS-waves (Gaiser, 1999), were applied. Each of the eight 2Cx2C sets was rotated into the preferred fast (PS_{11}) and slow (PS_{22}) directions (N135E and N225E) and stacked to create one set of 2Cx2C data for further analysis. This increased the fold and resulted in improved signal quality.

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 (Fig. 1).

Birefringence Analysis

One of the most important steps in using PS-waves for fracture detection is to quantify the overburden azimuthal anisotropic properties. 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. Another important property of the overburden is the vertical extent. One approach to estimate the 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 vertical time. Figure 2 shows an analysis between PS_{11} and PS_{22} data located at the well in the northern part of the 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 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 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 at about 1.3 s and then roughly follows a 30 ms PS_{22} time delay. In the absence of the upper 1.0 s of data, the base of the overburden can be interpreted at about 1.5 s. It represents an interval of relatively homogeneous, azimuthally anisotropic material with constant orientation confirmed by azimuth-supergather analyses. Notice that the trend increases to the 40 ms PS_{22} time delay contour at about 3.0 s, indicating an increase in S-wave birefringence.

Further processing of the overburden involves 2Cx2C rotation and Winterstein and Meadows (1991) layer stripping to remove the azimuthal anisotropic effects imparted on the PS-wave data. This can be accomplished over a time window from 0.0 to 1.6 s. After layer stripping, the data are in position for further analysis to determine principal S-wave directions and percent anisotropy for deeper intervals. Figure 3 shows the 2Cx2C-inline section that intersects the well at the vertical white line. PS_{11} and PS_{22} are the principal components and are aligned down to the base of overburden at about 1.6 s. The off-diagonal components (PS_{12} and PS_{21}) have been minimized to this same event.

One approach to analyze target horizons below the overburden is to interpret residual amplitudes on the PS_{12} and PS_{21} components spatially and temporally. These amplitudes can result when there are changes in the S-wave birefringence principal directions. Such changes may be too subtle to be quantified by traditional layer-stripping methods or by velocity ratios, but amplitudes are sensitive to these variations in S-wave properties and can give qualitative insights into regions where fracturing may be more intense and change orientation.

A more quantitative approach is to measure traveltimes between reflections bracketing targets for both the PS_{11} and PS_{22} waves in the volume in Figure 3. By comparing isochron differences between PS_{11} and PS_{22}, a spatial representation of percent anisotropy can be interpreted for lateral variations in fracture intensity. The assumption here is that there is little or no change in the orientation of the principal axes, since rotations are not involved.

The third approach, which is most quantitative, involves layer stripping below the overburden. 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 be interpreted as lateral variations in fracture orientation and intensity.

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 and limiting propagation azimuths 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 2Cx2C rotation. This increased fold helped improve the signal quality, but only after azimuth-consistent static corrections were computed and applied.

Vps_{11}/Vps_{22} velocity ratio analysis is a valuable tool to quantify the vertical extent of S-wave birefringence as a function of time. As this ratio varies in time, it 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. Three analysis techniques (residual PS_{12} and PS_{21} amplitudes, PS_{11} and PS_{22} traveltime isochrons, and layer stripping) provide a broad range of interpretation tools and attributes that can help identify lateral variations in fracture properties.

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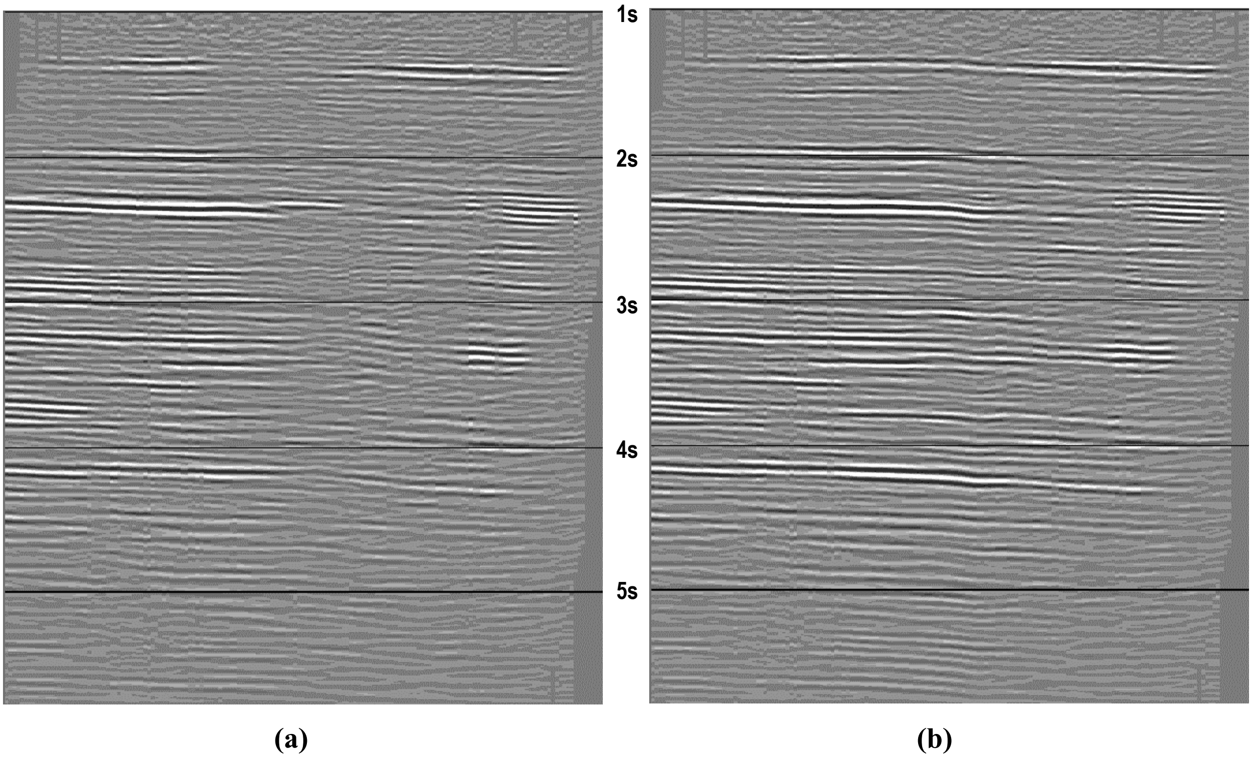

(a) (b)

Figure 1. (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.

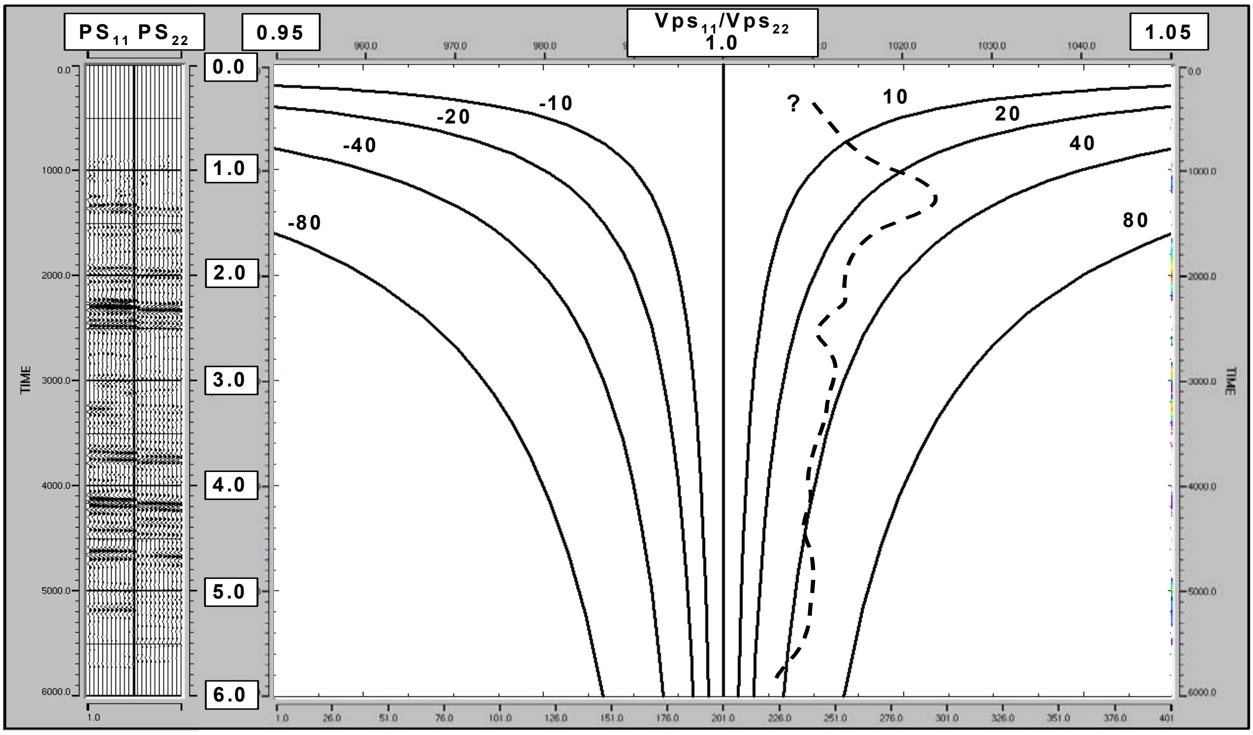

Figure 2. Average velocity-ratio analysis between the PS_{11} and PS_{22}.traces (left) located near the well in the northern part of the survey. The Vps_{11}/Vps_{22} ratio ranges from 0.95 to 1.05, time is two-way PS_{11}, and variable density represents positive cross-correlation coefficients between PS_{11} and PS_{22}. Contours indicate constant PS_{22} time delays and the dashed line shows the interpreted relationship between the split S-waves. The base of the overburden is interpreted at the maximum traveltime difference just below the event at 1.3 s.

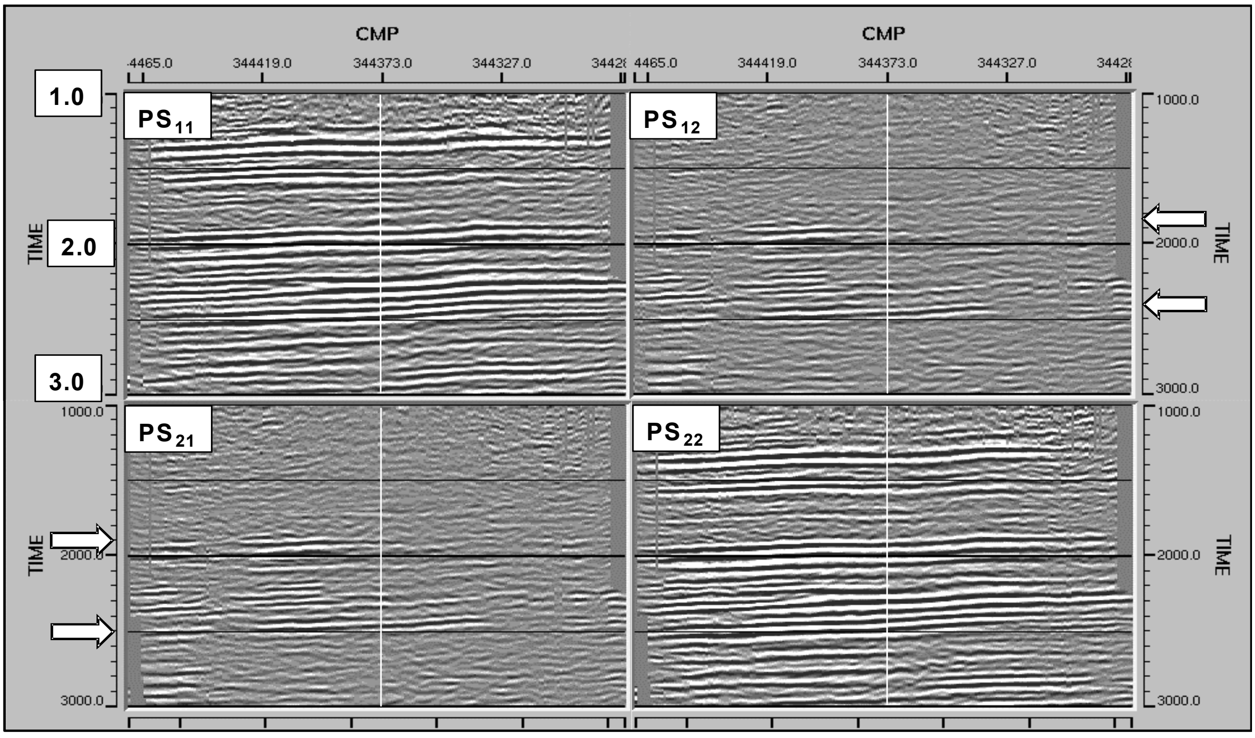

Figure 3. 2Cx2C inline section after Alford rotation and layer stripping the overburden. PS_{11} and PS_{22} are the principal components aligned through the overburden at about 1.6 s. These components are important for quantitative isochron analyses of percent azimuthal anisotropy. PS_{12} and PS_{21} are the off-diagonal components minimized through the overburden. Residual amplitudes below the overburden on PS_{12} and PS_{21} provide qualitative insights into changes in birefringence. The vertical white line indicates the location of the well and the Vps_{11}/Vps_{22} average velocity analysis in Figure 2.