Case History

3-D AVO analysis and modeling applied to fracture detection in coalbed methane reservoirs

Antonio C. B. Ramos* and Thomas L. Davis†

ABSTRACT

Over the years, amplitude variation with-offset (AVO) analysis has been used successfully to predict reservoir properties and fluid contents, in some cases allowing the spatial location of gas-water and gas-oil contacts. In this paper, we show that a 3-D AVO technique also can be used to characterize fractured reservoirs, allowing spatial location of crack density variations.

The Cedar Hill Field in the San Juan Basin, New Mexico, produces methane from the fractured coalbeds of the Fruitland Formation. The presence of fracturing is critical to methane production because of the absence of matrix permeability in the coals. To help characterize this coalbed reservoir, a 3-D, multicomponent seismic survey was acquired in this field. In this study, prestack P-wave amplitude data from the multicomponent data set are used to delineate zones of large Poisson's ratio contrasts (or high crack densities) in the coalbed methane reservoir, while source-receiver azimuth sorting is used to detect preferential directions of azimuthal anisotropy caused by the fracturing system of coal.

Two modeling techniques (using ray tracing and reflectivity methods) predict the effects of fractured coal-seam zones on angle-dependent P-wave reflectivity. Synthetic common-midpoint (CMP) gathers are generated for a horizontally layered earth model that uses elastic parameters derived from sonic and density log measurements. Fracture density variations in coalbeds are simulated by anisotropic modeling. The large acoustic impedance contrasts associated with the sandstone-coal interfaces dominate the P-wave reflectivity response. They far outweigh the effects of contrasts in anisotropic parameters for the computed models.

Seismic AVO analysis of nine macrobins obtained from the 3-D volume confirms model predictions. Areas with large AVO intercepts indicate low-velocity coals, possibly related to zones of stress relief. Areas with large AVO gradients identify coal zones of large Poisson's ratio contrasts and therefore high fracture densities in the coalbed methane reservoir. The 3-D AVO product and Poisson's variation maps combine these responses, producing a picture of the reservoir that includes its degree of fracturing and its possible stress condition. Source-receiver azimuth sorting is used to detect preferential directions of azimuthal anisotropy caused by the fracturing system of coal.

INTRODUCTION

Seismic amplitude variation with offset (AVO) technology has been used to predict reservoir properties and fluids. Most studies using this technology, however, have involved nonfractured reservoirs and two-component seismic data. In this study (Ramos, 1993), 3-D AVO analysis is performed on a multicomponent 3-D seismic data set and is used to better characterize the fractured coalbed methane reservoir at Cedar Hill Field, San Juan Basin, New Mexico (Figure 1). In this field, methane production is associated with the presence of enhanced fracture permeability in the coalbeds of the Fruitland Formation. High production trends are developed along the opened fracture sets of the coal. Two fracturing trends oriented northwest and northeast have been recognized in the area; they conform to the natural cleat system in the coal.
coals. Thickness variations and lateral continuity also affect methane production from the coals, which in general occur in thin layers, typically 1–6 m thick, interbedded with sandstones.

Table 1, modified from Ross (1992) and Domenico (1984), shows that Poisson’s ratio varies not only with lithology but also with compaction and pore fluid. In typical bright-spot environments, gas-charged sandstones have very low Poisson’s ratios compared with the surrounding shales, producing strong negative Poisson’s ratio contrasts ($\Delta \sigma = \sigma_2 - \sigma_1 < 0$) for the top of the reservoir. In contrast, coals have high Poisson’s ratios, which produce positive Poisson’s ratio contrasts for the top of the coals when the overlying sediments are consolidated sandstones. In addition to lithology and properties of pore fluids, Poisson’s ratio varies with the amount of clay minerals, pore pressure, porosity, temperature, and degree of fracturing. In this paper we focus on the analysis of the degree of fracturing.

At the basal part of the Fruitland Formation, high-velocity sandstones (with a compressional velocity of $\approx 3800$ m/s and a density of $\approx 2.57$ g/cm$^3$) occur above an important producing level of coals (with a compressional velocity of $\approx 2400$ m/s and a density of $\approx 1.5$ g/cm$^3$), producing a large acoustic impedance contrast. This large reflection coefficient is greatly dependent on Poisson’s ratio variations in the coal.

Gregory (1977) noticed that the presence of fractures in the rocks should cause an observable increase in the $V_P/V_S$ ratio (hence an increase in Poisson’s ratio). Poisson’s ratio contrasts have strong effects on AVO responses, since they are directly related to non-normal $P$-wave reflectivity. Variations in fracture density within the coal levels of the Fruitland Formation also have strong effects on $P$-wave reflectivity, since these variations control Poisson’s ratio contrasts at sandstone-coal interfaces. Laboratory measurements in vertical cores have shown that Poisson’s ratio in fractured coals increases by as much as 40% from a low to a high degree of fracturing (Figure 2). These measurements were made in the least fractured samples that were recovered from coring operations. From the analysis of Figure 2, one can conclude that the Poisson’s ratio contrast between sandstone and coal increases as the degree of fracturing in the latter increases. Therefore, this effect should have an impact on measurements of the AVO gradient obtained from surface seismic data from the top of the coals.

Because of vertical fracturing, the coals can produce azimuthal anisotropy. However, reflection coefficients derived for isotropic-isotropic and isotropic-anisotropic interfaces are not significantly different when velocity contrasts are high, i.e., when strong reflections, such as those from sandstone-coal interfaces, are present. Therefore, isotropic modeling using changes in Poisson’s ratio can provide an insight into the problem as good as that obtained through anisotropic modeling using variations in fracture density.

**Table 1.** Typical Poisson’s ratios in several types of rocks.

<table>
<thead>
<tr>
<th>Lithology/Pore fluid</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>U consolidated shale</td>
<td>0.38–0.45</td>
</tr>
<tr>
<td>Consolidated shale</td>
<td>0.28–0.34</td>
</tr>
<tr>
<td>U consolidated sandstone (brine)</td>
<td>0.30–0.35</td>
</tr>
<tr>
<td>Consolidated sandstone</td>
<td>0.17–0.26</td>
</tr>
<tr>
<td>High-porosity sandstone (brine)</td>
<td>0.35–0.42</td>
</tr>
<tr>
<td>Low-porosity sandstone (tight)</td>
<td>0.17–0.26</td>
</tr>
<tr>
<td>Gas-charged sandstone</td>
<td>0.10–0.16</td>
</tr>
<tr>
<td>Coal</td>
<td>0.37–0.45</td>
</tr>
</tbody>
</table>

**CEDAR HILL 3-D, THREE-COMPONENT SURVEY**

The Cedar Hill Field encompasses 125 km$^2$ and is located in the northwestern portion of the San Juan Basin, New Mexico (Figure 1). Three-dimensional, three-component seismic data for approximately 3.4 km$^2$ were acquired in the field by the Colorado School of Mines Reservoir Characterization Project. The survey layout (Figure 3) consisted of 11 receiver lines distributed in three swaths. Each swath consisted of five receiver lines spaced at 600 ft (182.9 m), with 50 three-component receivers each. Because of operational restrictions imposed by topography and vegetation, source positions were staggered in relation to the receiver locations and offset 60 ft (18.3 m) from receiver lines. Vibrator spacing was 120 ft (36.6 m) in all directions. The irregular source distribution caused irregular offset distribution in the common-midpoint (CMP) bins. Lower fold for the near-offset range (below 400 m) was obtained for CMP bins near the center of the survey area. Conversely, higher fold for the near-offset range and lower fold for the far-offset range (above 1000 m) were obtained for CMP bins near the edges of the survey area. Maximum fold (60) was obtained near the center of swath 3.

Figure 4 shows the time structure map of the lower producing horizon interpreted from the $P$-wave 3-D stack volume.

**FIG. 1.** Location map of Cedar Hill Field, San Juan Basin, New Mexico.

**FIG. 2.** Laboratory measurements for Poisson’s ratio in vertical cores.
Well locations and major faults also are shown in this map. A structural high of the lower producing coal develops in the eastern side of the survey area, which is cut by strike-slip faults trending east-west. Most faults mapped show a small vertical displacement, which increases as the structure deepens.

Preliminary data processing of the 3-D, three-component data included true amplitude recovery, deconvolution, refraction statics, CMP sorting, normal moveout (NMO) and residual statics. Square CMP bins 60 x 60 ft (18.3 x 18.3 m) were defined for the project. Totals of 102 east-west (cross-line) and 104 north-south (in-line) CMP tracks were created, generating 10 608 CMP bin locations. Nine adjacent CMP gathers (a 3 x 3 macrobin) were extracted from the CMP-sorted volume for prestack amplitude analysis. The location of the macrobins is shown in Figure 4. These macrobins have better offset and azimuth distribution than single CMP gathers, contributing to improved velocity and amplitude analyses. Maximum offset [6272 ft (1912 m)] was obtained at macrobin 8, and minimum offset [570 ft (174 m)] was obtained at macrobin 4.

Figure 5 summarizes the data processing sequence used to obtain AVO gathers from the 3-D, three-component seismic data of Cedar Hill Field. After two passes of 2-D velocity analysis and two passes of surface-consistent 3-D residual statics, the following steps were performed: trace editing, surface-consistent amplitude balancing, trace rebinning and summing within 100-ft (30.5-m) offset ranges, band-pass filtering, and phase rotation. Surface-consistent amplitude correction was a key step in the processing sequence, since there were important amplitude variations caused by source and receiver coupling differences. The final result obtained indicated that very little bias was introduced by the processing algorithms, so the approximate behavior of reflection coefficients could be derived from seismic amplitudes.

Figure 6 shows the P-wave data from macrobin 8 before and after applying the processing sequence shown in Figure 5. Raw data were composed of 380 traces (after trace editing). Processed data were rebinned and summed over 100-ft (30.5-m) offset ranges, so that they were reduced to 51 different offsets.
Figure 7 shows a selected portion of the $P$-wave data from macrobin 5 after processing. RMS amplitudes (shown on the bottom of Figure 7) were computed in a 20-ms gate centered around 0.605 s (top of coal reflection). A five-point running-average filter was applied to the amplitude data prior to fitting.

**Fig. 5.** Data processing sequence used to obtain the AVO gathers from the 3-D, three-component seismic data of Cedar Hill Field.

**Fig. 6.** $P$-wave data from macrobin 8 before and after the processing sequence shown in Figure 5. The original data included 380 traces (after trace editing); the final macrobin data were reduced (by rebinning and summing) to 51 traces. A 16- to 80-Hz band-pass filter and a $-270^\circ$ phase rotation were applied to the processed data set.

**Fig. 7.** $P$-wave data from macrobin 5. rms amplitudes (bottom) were computed for a 20-ms gate centered around 0.605 s, as indicated by the arrow (top of lower producing coal). Note the amplitude oscillations in the near-offset range.
Undulations in the normalized rms amplitude data are caused mainly by converted waves and coherent noise, which can contribute to distortion of the AVO estimates of gradient and intercept. A robust linear regression to obtain gradient and intercept AVO measurements, based on the criterion of the least absolute deviations, was used. This type of linear fit limited the damage caused by small wavelength oscillations in the amplitude data, especially oscillations caused by converted waves, which normally affect a narrow-offset range.

AVO MODELING

A horizontally layered earth model was generated using elastic parameters derived from sonic and density log measurements acquired at the Hamilton 3 well (Figure 8). Shear-wave velocities were derived for the entire well by using $P$- and $S$-wave sonic logs and $V_p/V_s$ ratios from laboratory measurements. A nisotropic parameters were derived using expressions derived in Thomsen (1995) in a model for aligned cracks in porous rocks. Laboratory measurements were taken from competent cores, probably the least fractured, from the Hamilton 3 well. These measurements indicate a substantial increase in the Poisson’s ratio of the coal layers with the degree of fracturing. Larger Poisson’s ratio contrasts are expected between sandstones and coals when the coals are considerably fractured.

In Cedar Hill Field, the material filling the crack system of the coals is expected to be gas or water. The presence of gas in the crack system of the coals, for lower confining pressures, reduces the $P$-wave velocity significantly. This effect is less important for $S$-wave velocity and contributes to lower $V_p/V_s$ ratios in gas-saturated conditions. Confining pressure at the level of the Fruitland coals is estimated around 1900 psi. The effects of changes in the saturated fluid and degree of fracturing were determined from laboratory measurements in vertical and horizontal cores with different fracture densities. Average $V_p/V_s$ ratios in vertical coal cores for brine-saturated samples were 1.97, 2.15, and 2.34, considering small, modest, and large fracture densities. The corresponding $V_p/V_s$ ratios for air-saturated cores were 1.85, 1.89, and 1.95. Therefore, $V_p/V_s$ ratios (and hence Poisson’s ratios) for the coal increased with the degree of fracturing and decreased with the presence of gas in the fracture system. Also, the percentage of change in $V_p/V_s$ ratios with the degree of fracturing was smaller in air-saturated than in water-saturated cores.

Figure 9 shows the effect of increasing the crack density of the coal on the $P$-wave reflectivity of the coal-sandstone interface (plotted in absolute values). A nisotropic parameters were modified according to the crack density magnitude. Fracture orientation was considered perpendicular to the seismic profile. There is little effect of crack density variations on $P$-wave reflectivity near vertical incidence. However, for intermediate incidence angles, up to 50°, as crack density increases, the magnitude of the AVO gradient also increases. When purely isotropic models are analyzed, variations in the crack density of the coal are simulated by reducing the Poisson’s ratio in the coal, therefore increasing the Poisson’s ratio contrast at the interface and consequently affecting the AVO gradient in the same way (large $\Delta \alpha$ values correspond to large AVO gradients). The effect of changing the velocity contrast between the upper (sandstone) and lower (coal) layers but keeping $\Delta \alpha$ constant is that of an overall increase in the reflectivity response (and in the AVO intercept) as the velocity contrast is increased.

Figure 10 shows a synthetic AVO gather computed with the reflectivity method, which included all possible reflected events from the earth model. The gather is NMO corrected, and the plot of normalized rms amplitudes for the coal reflection is shown on the bottom of Figure 10. A strong converted wave energy ($P$-$SV$) remains undercorrected after NMO and interferes with the coal reflections (between 0.55 and 0.61 s) at short and intermediate offsets, producing oscillations in the AVO response. $P$-$SV$ converted waves have slow stacking velocity and therefore might easily be confused with multiple $P$-waves. However, converted waves have zero amplitude at zero offset, so that events with significant amplitudes at zero offset can be classified as nonconverted waves.

A synthetic AVO gather including only primary events and computed through isotropic ray tracing is shown in Figure 11. The plot of normalized rms amplitudes for the coal reflection has a considerably smaller scatter of amplitudes than that of

![Figure 9](image9.png)  
Figure 9. Effect of increasing the crack density of the coals on $P$-wave reflectivity. A nisotropic ray tracing modeling was used to generate the responses.

![Figure 8](image8.png)  
Figure 8. Velocity and density models from the Hamilton 3 well.
Figure 10. A P-wave synthetic AVO gather computed with the reflectivity method and plot of normalized amplitudes for the event corresponding to the lower producing coal (indicated by the arrow near 0.6 s). Note how the converted waves were undercorrected after NMO and persisted throughout the record, producing oscillations in the amplitude response. A 10- to 50-Hz band-pass filter was applied to this synthetic gather.

Figure 11. Synthetic isotropic AVO gather computed with ray tracing and corresponding to macrobin 5. RMS amplitudes were computed for a 20-ms gate centered in the event around 0.6 s.

Figure 12. Synthetic AVO gather computed with ray tracing and including a P-SV converted wave generated in the overburden. Note the interference produced by the converted wave (event with undercorrected NMO) and the corresponding amplitude oscillations in the near offsets. A 10- to 50-Hz band-pass filter was applied to this synthetic gather.
where \( \lambda \) is the wavelength of the seismic pulse at the peak frequency, or 8 ms in terms of traveltime. Coal thickness does not vary greatly over the survey area, averaging 16 ft (4.9 m, or 2.2 ms in terms of traveltime) for the basal part of the Fruitland coal (Shuck, 1993). The measured amplitudes at the time gate of the lower producing zone actually correspond to an averaged medium composed of coal and interbedded noncoal materials (typically sands and shales). However, for the wavelet bandwidth used the contribution of the sandstone-coal interface is greater than the contribution of other interfaces in this zone.

The importance of detecting how much deviation the tuning effect may produce in the AVO estimates is related to the fact that one can erroneously interpret a larger AVO gradient as being the result of a larger crack density in the coal, when this larger estimate is actually caused by interferences resulting from tuning. Figure 13 shows how the tuning effect has an impact on the magnitude of the AVO estimates. In this case, the computation of the AVO estimates was done by fitting the maximum \( P \)-wave amplitudes with respect to \( \sin^2 \theta \) (where \( \theta \) is the average angle of incidence and refraction, determined from ray tracing at the top of the coal layer). As the thickness of the coal layer is decreased, the gradient reaches a maximum magnitude at about 4 m (which may be shifted to a lower thickness as the bandwidth of the wavelet is increased). Considering that the thickness of the lower producing coals averages about 5 m in the survey area, the maximum deviation to a larger gradient will be about 4%. This deviation is overridden by the effect of large crack densities on the AVO gradient. In addition, because thickness variations are small in the survey area, the tuning effect should be similar for most of the data under analysis; i.e., the tuning effect should produce similar changes in the magnitude of the AVO gradient in all CMP locations. The importance of this observation is that the relative comparison of AVO gradients, for the purpose of interpreting crack density variations in the coals, is still valid. However, if the area under consideration is quite large and thickness variations are significant, then a careful interpretation and tuning correction should be considered. Good well control and isopach maps will be important in the tuning effect compensation.

AVO ANALYSIS

The normalized \( P \)-wave rms amplitude data for the reflection at the top of the lower producing coal, corresponding to each macrobin, were plotted against \( \sin^2 \theta \) (where \( \theta \) is the average angle of incidence and transmission, computed from ray tracing through the earth model). The angle \( \theta \) was limited to \( 33^\circ \), in accordance with the linearized expressions for \( P \)-wave reflection coefficients (Shuey, 1985). The actual AVO response was considered as the expression

\[
R_a(\theta) = R_0 + G \sin^2 \theta, \tag{1}
\]

where \( R_0 \) is the AVO intercept and \( G \) is the AVO gradient. A robust linear regression was used to obtain estimates of \( R_0 \) and \( G \).

Figure 14 shows the plots of normalized amplitude as a function of \( \sin^2 \theta \) for macrobins 3, 5, and 8. The angle \( \theta \) in each graph was computed from ray tracing through the earth model for the Hamilton 3 well. Only amplitude values corresponding to \( \theta \leq 33^\circ \) were considered for fitting, in agreement with the linearized model shown in equation (1). In some macrobins (such as macrobin 3), the maximum angle of incidence with
useful amplitudes was less than 33°. The $P$-wave amplitudes of each macrobin were normalized and scaled by the normal incidence reflection coefficient ($R_0 \approx -0.5$). This procedure was applied assuming that the measured amplitudes were scaled versions of the reflection coefficients. The scaling factor was the same in all graphs, so that it did not affect the comparative analysis. Despite the use of a scaling factor, the AVO estimates obtained from this analysis were relative values and did not correspond to direct measurements of rock properties.

Poststack amplitude anomalies result from strong increases in $P$-wave impedance, which can be related mainly to low velocity or low density in the coal. Figure 15 shows the poststack rms amplitude map for the top of the lower producing coal, obtained from the $P$-wave 3-D stack volume, with deconvolution and migration applied. Major faults shown in this map were interpreted from Figure 4. Large amplitude values with respect to the background amplitudes are found in the eastern side of the area, more precisely in the area limited by two strike-slip faults. Considering these high amplitudes as related to only low velocity in the coal, the anomalies can be an indication of a reduction in the effective stress, which in turn can be related to high reservoir fluid pressures.

The combined effect of Poisson’s ratio variations and velocity contrasts associated with highly fractured coal zones can be estimated as the product of the AVO gradient and the AVO intercept. Figure 16 shows the AVO product map from the linearized estimates of gradient and intercept obtained at each macrobin location. A large AVO product (and AVO gradient) is found in the area of macrobin 5. This map shows reasonable agreement with the $P$-wave relative-amplitude map for the top of the lower producing coal (Figure 15). There is also reasonable agreement with the crack density map determined from time-delay anisotropy estimates and from reflection amplitudes obtained from poststack shear-wave data (Shuck, 1993). The central and southwestern portions of the survey area correspond to a strike-slip fault zone, which possibly caused stress relief and a higher degree of fracturing in the coal. This was possibly the case at the Hamilton 3 well, which was drilled twice, using the cavity completion technique the second time. This technique opened a hole and fractures around the well and improved the connection with fracture zones away from the well. Gas productivity increased significantly after this technique was applied. There are also indications (Johnson, 1991) in the

![Fig. 15. Poststack amplitude map for the top of the lower producing coal, obtained from the $P$-wave stack volume.](image)

![Fig. 16. AVO product map for the lower producing horizon based on macrobin analysis from the Cedar Hill Field 3-D, three-component survey. Macrobin locations are shown as black squares. Major faults in the area, determined from $P$-wave interpretation, also are shown.](image)
Cedar Hill Field area of severe differential compaction, which affects the fracture permeability of the coal and consequently the AVO response. Figure 17 shows the relative Poisson’s ratio variation for the top of the lower producing coal in the area. This estimate, also known as Poisson’s reflectivity, was computed from the AVO gradient and intercept estimates at each macrobin location using Hilterman’s approximation described in Castagna (1993) and written as

\[ R_p(\theta) \approx R_0 \cos^2 \theta + 2.25 \Delta \sigma \sin^2 \theta. \]  

(2)

This approximation considers that the average Poisson’s ratio of the two media involved is equal to 1/3, which is approximately the value for the sandstone-coal interface. Modifying this approximation to look like equation (1) and extracting \( \Delta \sigma \) from the resulting gradient results in

\[ \Delta \sigma = \frac{R_0 + G}{2.25}. \]  

(3)

As with the AVO product map in Figure 16, large variations in Poisson’s ratio are found along a northeast trend, with high values near the center of the area.

To check the validity of the straight-line fit and the amount of oscillation in the amplitude data, a statistical analysis from the robust regression analysis was carried out. The mean absolute deviation from the fitted line for each macrobin is shown in Figure 18. The small values for macrobins 3 and 5 confirm that these were the most reliable. The limitation in offset range is also a factor that should be taken into account. Macrobins with very limited offset ranges should be assigned a smaller degree of reliability, despite the measure of absolute deviation.

The maps shown in Figures 16 and 17 were based on macrobin computations and therefore are rough approximations of the possible fracture density distribution in the area. Figures 19 and 20, respectively, show the corresponding AVO product and Poisson’s ratio variation maps for the top of the lower producing coal, obtained for every bin in the prestack volume. Both maps are similar in most features, particularly with respect to the high values for the AVO product and Poisson’s reflectivity near the center of the survey area. This anomaly does not match the larger anomaly found in the poststack amplitude map (Figure 15). The main reason for this difference is the fact that these maps are both related to the AVO gradient and therefore are functions of the amplitude decay with offset and not the average amplitude found in the stack. It is believed that the strike-slip movement along the east-west–trending fault near cross-line 50 was responsible for stress relief, which may have increased the opening of fractures in the central portion of the area, therefore producing large Poisson’s reflectivity anomalies.

**AZIMUTHAL AVO ANALYSIS**

A azimuth and offsets in a 3-D seismic survey depend on the acquisition geometry (number of receiver lines, receiver and source spacing, receiver line spacing, and so forth) and logistic factors. The latter were particularly important in the survey area (as shown in Figure 3) because they caused highly variable offset and azimuth distributions for most CMP gathers.

The effect of changes in fracture orientation (with respect to the survey line) on reflection coefficients is known to be more significant for \( S \)-waves than for \( P \)-waves. However, the signal-to-noise ratio constraints on prestack data are also larger in \( S \)-wave data than in \( P \)-wave data. To model the effect of fracture orientation on \( P \)-wave data, we considered a simple interface model, composed of an isotropic layer (unfractured) over an anisotropic layer (fractured). The latter was assumed to be a vertically fractured medium, which can be represented as a transversely isotropic medium with a horizontal axis of symmetry. The analysis of the reflection coefficient responses produced from this model showed that slightly larger \( P \)-wave amplitudes at larger incidence angles occur whenever the seismic profile parallels the fracture strike.

A azimuthal AVO analysis was carried out on the \( P \)-wave macrobin data with the objective of detecting any preferential trend of \( P \)-wave anisotropy. Analysis of the macrobin amplitude data showed that unbalanced offset and azimuth distributions affect AVO responses. Macrobins in the center of the survey area, such as macrobin 5, were chosen for the azimuthal analysis because of their improved offset and azimuth distributions.
compared with macrobins close to the edges of the survey area. After trace editing and true amplitude processing, the data were sorted in three 40°-wide azimuth sectors. These sectors were chosen according to the preferential orientation of the S1 (fast shear-wave) polarization direction, which aligns predominantly northwest-southeast (N40W) in a large part of the survey area (Shuck, 1993). Figure 21 shows the P-wave data from macrobin 5 sorted according to the three azimuth sectors, in the northwest (60° to 20° azimuth), north-south (20° to 20° azimuth), and northeast (30° to 70° azimuth) directions. The northwest and north-south azimuth sectors produce similar AVO responses, which are also similar to the AVO response obtained with all traces in the macrobin (Figures 6 and 7). Amplitudes in the north-south direction are slightly higher than those in the northwest-southeast direction, resulting in a smaller gradient and suggesting that fracture orientation might

Fig. 19. AVO product map for the top of the lower producing coal, obtained from the P-wave prestack volume. Note the high amplitudes near the center of the survey area, which do not correspond to the poststack amplitude anomalies shown in Figure 15.

Fig. 20. Poisson’s ratio variation map for the top of the lower producing coal, obtained from the P-wave prestack volume. Note the similarities with the AVO product map shown in Figure 19.
be along the north-south azimuth sector in the area of macrobin 5. The northeast azimuth sector has a poor offset distribution and therefore produces a biased AVO response.

Figure 22 shows bin-azimuth traces for macrobin 5. These bin-azimuth traces were obtained by partially stacking the data in approximately 5° source-receiver azimuth ranges, instead of 100-ft (300 m) offset ranges, as shown in all previous displays. There are 37 traces, each one indicating a particular source-receiver azimuth range. Trace 1 indicates azimuth to the west, and trace 19 indicates source-receiver paths close to the north-south direction. If the offset and azimuth distributions were perfect (same number of traces in all offset and azimuth ranges) and the amplitudes were perfectly balanced (corrected for array effects and surface-consistent amplitude variations), this display could give us an indication of the characteristic directions of azimuthal anisotropy in the medium. In this sense, the larger amplitudes observed in traces 17 to 20 indicate that the fracture system is oriented between northwest-southeast and north-south directions. This result agrees with the polarization of the fast shear wave (Shuck, 1993) and the butt cleat orientation found in the coals. The major limitation in this case is the fact that offset and azimuth distributions are not perfect, so this technique cannot be extended to all macrobins.

To support the azimuthal analysis using bin-azimuth traces, amplitudes for all traces in macrobin 5 were also plotted in polar diagrams. The azimuthal plot of amplitudes for macrobin 5 is shown in Figure 23. In this case, the rms amplitude in a 20-ms gate around the target was computed for each trace in the macrobin. Each amplitude is plotted in its corresponding position in terms of azimuth (azimuthal direction) and offset (radial direction) but in a Cartesian coordinate frame. The amplitudes are presented in gray-scale contours, with larger amplitudes corresponding to dark gray and black. Confirming the results of Figure 22, slightly larger values are found toward north and northwest, indicating that fractures may have opened along these directions. The fault pattern in Figure 4 shows an east-west–trending major fault near macrobin 5. A’s mentioned in the preceding section, strike-slip movement along this fault may have caused the stress relief that opened fractures in the coals along north and northwest directions.

**DISCUSSION**

Three-dimensional AVO analysis requires careful data processing and sophisticated forward wave propagation modeling, including true-amplitude ray tracing and reflectivity algorithms capable of producing synthetic seismograms in anisotropic layered media. The data-processing phase must include two major processes: true-amplitude signal recovery and surface-consistent amplitude balancing. In addition, careful
editing is required, particularly for land data sets, which may contain considerable coherent noise contamination. Without these processes it is impossible to validate AVO measurements.

Statistical analysis of the data is also quite important. A measure of the correlation coefficient of the straight-line fit through the data provides an opportunity to weight the AVO attributes measured in the process. In this study, the mean absolute deviation was taken as a measurement of relative reliability. Furthermore, when the data have irregular spatial sampling, e.g., are lacking near or far offsets, the offset range present in the input data should be used as a quality factor for the AVO analysis.

Offset and azimuth distributions affected the azimuthal AVO analysis considerably. Apparently, amplitude variations in data partially stacked by offset and displayed in different azimuth sectors are not easily related to changes in P-wave reflectivity, unless the data are sufficiently sampled in the offset and azimuth domains. If the data have unbalanced offset and azimuth distributions, the amplitude variations can be biased. The controlling factors in this case are the fold per offset range and the fold per azimuth range.

Petrophysical measurements have shown that the Poisson’s ratio in coal cores increases with the degree of fracturing in the coals. Therefore, an increase in Poisson’s ratio contrasts is expected between sandstones (which encase the coals) and coals when the latter are considerably fractured. This increase affects the angle-dependent P-wave reflectivity at the top of the coals.

Characterization of fracture density variations in coal using AVO analysis is feasible, but careful processing and improved acquisition schemes have to be applied. From the data used in this study, a large Poisson’s reflectivity anomaly was detected near the center of the survey area, which is believed to correspond to an area of large fracture density in the coals.

CONCLUSIONS

This study demonstrates how prestack P-wave amplitude data can be used to characterize fractured reservoirs. For Cedar Hill Field, mapping zones of large AVO gradients corresponds to mapping zones of large Poisson’s ratio contrasts from sandstone-coal reflections. Core and well log data from Cedar Hill Field have shown that these zones correspond to higher fracture densities in the coal layers. The integration of 3-D, three-component seismic data and AVO analysis constitutes a new approach for characterizing fractured reservoirs. The application of this new approach can reduce risk and improve hydrocarbon productivity from fractured reservoirs.

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Fig. 23. A azimuthal plot of amplitudes for macrobin 5. The horizontal and vertical axes represent the Cartesian coordinate frame of a polar plot of amplitudes. The origin (0, 0) corresponds to the source location for all traces in the macrobin. Amplitudes were plotted at their corresponding source-receiver offset and azimuth. Large amplitude values (darker gray) parallel north and northwest, indicating that there may be open fractures or stress relief along these directions. Major fault patterns and the location of macrobin 5 are shown in Figure 4.
REFERENCES


