Vector correlation of AVAz and curvature attribute—Application to Mississippian Tripolitic Chert, Osage County, Northeast Oklahoma
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Summary

Chert is an unconventional reservoir rock that has been developed successfully in west Texas, Oklahoma, California and Canada. Tripolitic chert is a diagenetically altered form of cherts which show high porosity and low resistivity. The Mississippian tripolitic chert is currently an exploration and development objective through-out southern Kansas and northern Oklahoma, including our survey area of Osage county. As one of the most fully developed unconventional plays in North America, knowing the orientation and intensity of the present day horizontal stress direction is critical to both the placement and completion of horizontal wells. In our study, we wish to determine the correlation, if any, between structural deformation as measured by curvature and coherence and the present day stress orientation as measured by amplitude vs. azimuth (AVAz) analysis.

We map structural features along top Mississippian Lime horizon using geometric attributes and find a high correlation between low coherence and most negative curvature fault lineament. We migrate our data into azimuthal bins and compute changes in amplitude with azimuth. Such AVAz volumes are commonly used to predict the orientation of horizontal stress.

Faults are known to modify the subsurface stress regime. We map faults using both the strike and magnitude of the most-negative principal curvature and visually correlate them to strike and magnitude of AVAz. To quantify this correlation, we compute a vector correlation between AVAz and most negative curvature, and find high correlation between structural faults and low anisotropy intensity indicating that the Mississippian Lime are most controlled by diagenetically altered fractures.

Introduction

The Mississippian tripolitic chert is formed at the unconformity between the Pennsylvanian Cherokee Shale and Mississippian Lime in north-central Oklahoma and south-central Kansas. Rogers and Longman’s (2001) analysis of Mississippi chert core shows that chert have low density and high porosity, exhibiting vugs, nodules, and fractures with little remnant of the original depositional fabric. These properties make the Mississippian chert a good unconventional reservoir rock. The chert is also controlled by diagenetically altered fractures. The goal of this work is to see if there is a correlation between the lineaments seen in structural attributes and the stress regime measured by AVAz.

Indirect measures of fractures including geometric attributes over post-stack data such as coherence and curvature are commonly used in seismic interpretation (Chopra et al., 2007; Blumentritt et al., 2006; Thompson et al. 2010, Guo, 2010). Amplitude vs. Azimuth (AVAz) (Rueger, 1998; Goodway et al., 2007b) and Velocity vs. Azimuth (VVaz) (Sicking et al., 2007; Roende et al., 2008; Jenner, 2001) are common measures of present day stress orientation. In the presence of natural fractures, the reflectivity response parallel to fracture strike is close to that of the unfractured rock matrix (Rueger, 1997).

Hunt et al. (2011) found that a combination of AVAz and curvature are best correlated to fractures directly measured by horizontal image logs and microseismic measurements. Guo et al. (2010) visually correlated VVaz to the strike of the most negative curvature and found a strong rotation between the two across the strike-slip Mineral Wells fault at the Ellenburger Dolomite level beneath the Barnett Shale.

In this study, we extend the work by Guo et al. (2010) through the use of AVAz and a more quantitative correlation. We migrate our seismic data into different azimuths using a binning approach described by Perez and Marfurt (2008). This new binning allows us to identify the image contribution from out-of-the-plane steeply dipping reflectors, fractures, and faults. Next we compute AVAz anisotropy from a suite of azimuthally limited prestack gathers, followed by fitting sinusoids to the four seismic amplitude volumes to resulting in an AVAz analysis. We then compare the AVAz images to geometric coherence and curvature attributes over the fully stacked volumes.

Method

Perez and Marfurt (2008) proposed an azimuthal binning approach to Kirchhoff prestack migration that sorts output by the azimuth of the average travel path from surface midpoint to subsurface image point, rather than the azimuth between source and receiver (Figure 1). This binning allows us to identify the image contribution from out-of-the-plane steeply dipping reflectors, fractures, and faults.
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Figure 1. New azimuthal binning (after Perez and Marfurt, 2008).

Figure 2. Example of a good sinusoidal fit (a) and bad one (b) by using four samples (after Zhang et al. 2011).

Rueger’s (1996) equation for AVAz can be written as

\[ R(\theta, \phi) = A + [B_{\text{iso}} + B_{\text{aniso}} \cos(2(\phi - 2\psi))] \sin^2 \theta \]  

(1)

where \( R(\theta, \phi) \) is the reflectivity at angle of incidence \( \theta \) and azimuth \( \phi \). In the absence of anisotropy, \( B_{\text{aniso}} = 0 \), and equation (1) reverts to the well-known AVO equations in terms of slope, \( B_{\text{iso}} \) and intercept, \( A \). Note the azimuthal anisotropy plays an increasingly stronger role larger angles of incidence, as indicated by the \( \sin^2 \theta \) coefficient. It is critical to account for VVAz effect prior to application of AVAz. We therefore “register” the different azimuthally limited volumes by picking the top Mississippi Lime and flattening.

AVAz has a magnitude, \( B_{\text{aniso}} \), and an azimuth, \( \phi \). The most negative curvature has a value \( k_z \), and a strike, \( \psi_{\text{max}} \). Both attributes are thus vectors. Outcrop work by White (2013) and others shows a strong correlation between curvature and natural fractures. We also know that natural fractures give rise to anisotropy. Guo et al. (2009) found correlations between curvature and velocity anisotropy, with anisotropy south and north of the Mineral Wells strike slip fault to be parallel and perpendicular to the fault, consistent with outcrop analogues and finite element models. Such an explicit relationship suggests the use of vector correlation between anisotropy, \( \mathbf{a} \), and curvature \( \mathbf{c} \). Using vector arithmetic, we can compute the colinear component

\[ \mathbf{a} \cdot \mathbf{c} = a_x c_x + a_y c_y \]  

(2)

and the orthogonal component:

\[ \mathbf{a} \times \mathbf{c} = a_x c_y - a_y c_x \]  

(3)

to construct components of a vector correlation, where \( a_x \) and \( a_y \) are \( x \) and \( y \) components of vector \( \mathbf{a} \) and \( c_x \) and \( c_y \) are \( x \) and \( y \) components of vector \( \mathbf{c} \). The components of the vector correlation are then

\[ r_{\text{colinear}} = \frac{\sum_{j=1}^{J} (a_x'c_x + a_y'c_y)}{\sqrt{\sum_{j=1}^{J} (a_x'^2 + a_y'^2)\sum_{j=1}^{J} (c_x'^2 + c_y'^2)}} \]  

(4)

and

\[ r_{\text{orthogonal}} = \frac{\sum_{j=1}^{J} (a_x'c_y - a_y'c_x)}{\sqrt{\sum_{j=1}^{J} (a_x'^2 + a_y'^2)\sum_{j=1}^{J} (c_x'^2 + c_y'^2)}} \]  

(5)

where

\[ \| \mathbf{r} \| = (r_{\text{colinear}}^2 + r_{\text{orthogonal}}^2)^{\frac{1}{2}} \]  

(6)

and

\[ \varphi = \arg(r) = ATAN2(r_{\text{orthogonal}}, r_{\text{colinear}}) \]  

(7)

Thus \( \| \mathbf{r} \| \) and \( \varphi \) are correlation coefficient value and strike.

Applications

The Mississippian chert was formed from Osagean (Mississippian) chert limestone during the exposure of those limestones at the unconformity as shown in Figure 3a. The chert is a diagenetically altered interval of Osagean cherty limestones at the unconformity as shown in Figure 3a. The rock unit is a weathered and detrital, highly porous chert, and serves as a significant hydrocarbon reservoir rock in north central Oklahoma in Figure 3b. Trapping mechanisms for hydrocarbons in the chert reservoirs are faults, structural closures, and porosity pinch outs caused by truncation and diagenesis on the flank of structural highs (Rogers, 2001).
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Figure 3. (a) Stratigraphic column of Osage County, Oklahoma. (b) Clasts of chert are visible as angular discolored forms in these typical core samples from the chert. Samples are from the middle of the zone and suggest small-scale debris flow textures. (After Rogers, 2001).

Figure 4. (a) Time structure map of Mississippian Chat, (b) Vertical slice through stacked volumes along profile AA'. Figure 4a shows the time structure map on top of Mississippian Chert interpreted from the full stacked migrated seismic volume. White arrows denote the fault lineaments. Figure 4b shows vertical slice AA', where white block arrows indicate three structurally low features. Their lateral extent represents diagenetically altered fractures or faults. Figure 5 shows four azimuthally limited stacked volumes. Note how amplitude changes for different azimuths along the structurally low features indicated by white arrows.

Figure 5. Vertical slice through stacked volumes along profile AA' from (a) azimuth 0°, (b) 45°, (c) 90°, (d) 135°. White arrows denote faults. Note difference of faults lineaments from different azimuth stacked volume.

Figure 6a and b shows horizon slices along the Mississippian Lime through most negative curvature and coherence. White arrows denote fault lineaments. In addition, there is high correlation between these two attributes, which is consistent with the previous faults interpretation from the vertical slice. Figure 7a shows the same horizon slice through AVAz anisotropy intensity. Note the anisotropy low in the fault area. Figure 7c illustrates this correlation by co-rendering AVAz anisotropy intensity and most negative curvature. In addition, there is also high correlation between fault and low anisotropy intensity from figure 8d, which violates structural fractures caused anisotropy, so we can conclude that fractures from Mississippian tripolitic chert is not only structural caused, which is consistent with that Mississippian tripolitic chert are controlled by diagenetically altered fractures. Figure 7b shows horizon slice through max anisotropy azimuth, which denotes west-east direction horizontal stress, which shows perpendicular relationship with north-south direction fault lineament, note that Mississippian tripolitic chert is compartmentalized with the fault lineament.

Figure 6. Horizon slices along top Mississippi Lime through (a) most negative curvature, (b) coherence, (c) most negative curvature co-rendered with coherence.
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Figure 7. Horizon slices along top Mississippi Lime through (a) AVAz anisotropy intensity, (b) anisotropy maximum azimuth, (c) anisotropy intensity co-rendered with most negative curvature, (d) anisotropy intensity co-rendered with coherence. High anisotropy (yellow and red) appears in areas that have undergone less faulting (higher coherence) and less folding (near zero curvature).

Figure 8. Horizon slices along top Mississippi Lime through (a) strike of the most negative curvature modulated by its value, (b) strike of AVAz anisotropy modulated by its value, (c) correlation of new vector attributes modulated by its value. Correlation window has a radius of 1100 ft. White arrows denote fault lineaments.

Conclusions

The seismic geometric attributes can be a powerful tool to image structural features for Mississippian tripolitic chert. Good correlation of high coherence and negative curvature highlight the structural controlled faults zone from Mississippian tripolitic chert. AVAz anisotropy azimuth shows maximum EW stress field, which indicates perpendicular relationship with big fault lineaments. High correlation between structural faults and low anisotropy intensity indicates that Mississippian tripolitic chert are controlled by diagenetically altered fractures.

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EDITED REFERENCES
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REFERENCES


