VVAZ analysis for seismic anisotropy in the Altamont-Bluebell Field
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Summary

The 3D seismic data was acquired within Bluebell Field, the eastern portion of Altamont-Bluebell field in northeastern Utah. Altamont-Bluebell field is within the Uinta Basin, and is considered an unconventional reservoir in the sense that natural fractures act as fluid storage and conduits in the tight sandstones and carbonates. Information related to fracture orientation and intensity is vital for the development of such reservoirs. Azimuthal variations of P-wave velocities can be a valuable tool for fracture information. Therefore, this paper utilizes Velocity Variations with Azimuth (VVAZ) to estimate the direction and intensity of fractured-induced anisotropy within one of the reservoirs, Upper Green River formation.

VVAZ inversion method is applied based on the elliptical NMO equation for TI media that was derived by Grechka and Tsvankin (1998). Our code has been tested on a 3D physical modeling dataset Al Dulaijan et. al. (2015). Isotropic NMO velocities are used along with azimuthally variant time residuals to estimate fast and slow NMO velocities and their direction. Hampson-Russell suits VVAZ has also been implemented and results are compared in the report. An interval Dix-type properties were calculated to minimize the effect of the overburden.

Introduction

Bluebell-Altamont field is located in northeastern Utah in the Uinta basin. The Uinta basin is an asymmetric east-west trending basin with a south flank that slopes gently. The north flank is bounded by east-west trending Uinta Mountains. The Bluebell-Altamont field is located in the northern-central part of the basin (Figure 1). Production is from Tertiary sandstones, shales and carbonates. There are three main targets in the field: Upper Green River, Lower Green River, and Wasatch/Flagstaff (Lynn et. al, 1995). Bluebell-Altamont field is unconventional in the sense that natural fractures act as storage and conduits in the tight sandstones and carbonates. Bluebell field is the eastern portion of the Bluebell-Altamont field. Its cumulative production is 336 MMBO, 588 BCFG, and 701 MMBW. The objective of this study is to identify density and direction of fractures to help in determining well spacing to existing wells needed to effectively drain the remaining hydrocarbon reserves in the Bluebell field, and to identify new drilling opportunities (Adams et. al, 2014).

Seismic data acquisition and processing

The 3D seismic data was acquired over an area of 35 square miles within Bluebell field in 2010. Figure 2 shows a basemap of 3D seismic data, with color indicating fold. Two vibrators were used for each source point and an array of six geophones over a 6’ circle were used for each channel. The receiver and source intervals are 220’. The receiver lines are oriented E-W and spaced 1100’, while source lines are oriented N-S and spaced 660’. Bin size is 110’x110’, and the nominal fold is 240. In addition, a zero-offset VSP survey location is indicated by a black circle.

Refraction statics were applied. Heavy noise were observed and suppressed in multiple domains (i.e., shot, CDP, inline-azimuth-shot line). Also, spherical divergence correction, surface-consistent amplitude corrections, and deconvolution were applied. The zero-offset VSP was used to calculate Q that later was accounted for in the 3D seismic data processing. Isotropic velocity analysis at one-mile intervals and NMO corrections were followed by residual statics. Second pass of velocity analysis at half-mile intervals was
followed by another pass of residual statics. After muting, the data were stacked.

Upper Green River consists of lacustrine carbonate and clay, while Mahogany bench consists of shale and is a very strong marker (Lucas and Drexler, 1976). Mahogany bench is within the Upper Green River formation. The fracture analysis carried in this paper is on the interval from Upper Green River top to Mahogany bench. Unlike Amplitude Variations with Azimuth AVA Z methods, VVAZ methods use the base of the target rather than the top of the target.

VVAZ method

Grechka and Tsvankin (1998) showed that azimuthal variations of NMO velocities can be estimated by an ellipse in the horizontal plane for arbitrarily anisotropic and inhomogeneous media under the following assumption. First, traveltimes exist at most azimuths. A case of salt domes creating a shadow zone at a specific azimuth violates the second assumption. The second assumption is common in seismic data processing steps, such as CMP binning and stacking. That is traveltimes can be described by a Taylor series expansion of \( t^2 \) in powers of \( x_{\phi}^2 \), where \( t \) and \( x_{\phi} \) are traveltimes and source-receiver offset at specific azimuth. Lastly, traveltimes increase with offset at all azimuths. Those assumptions are nonrestrictive in most cases. Grechka and Tsvankin (1998) derived an elliptical NMO equation for TI media where source-receiver offset do no exceed the depth of the reflector. Hyperbolic NMO can be approximated by:

\[
T^2 = T_0^2 + \frac{x^2}{V_{NMO}(\phi)}
\]

where

\[
\frac{1}{V_{NMO}(\phi)} = \frac{1}{V_{fast}^2} \cos^2(\phi - \beta_z) + \frac{1}{V_{slow}^2} \sin^2(\alpha - \beta_z)
\]

where \( T \) is the total two-way traveltimes, \( T_0 \) is the zero-offset two-way traveltimes. \( x \) is the offset, \( V_{fast} \) and \( V_{slow} \) are the fast and slow NMO velocities respectively. \( \beta_z \) is the azimuth of the slow NMO velocity, while \( V_{NMO}(\phi) \) is the NMO velocity as function of the source-receiver azimuth (Figure 8).

Equation (2) can be written as:

\[
\frac{1}{V_{NMO}(\phi)} = W_{11} \cos^2(\phi) + 2W_{12} \cos(\phi)\sin(\phi) + W_{12} \sin^2(\phi)
\]

where \( W_{11}, W_{12}, \) and \( W_{22} \) are the ellipse coefficients that are related to the slow and fast NMO velocities and to the azimuth of the slow NMO velocity by

\[
\frac{1}{V_{fast}^2} = \frac{1}{2} (W_{11} + W_{22} - \sqrt{(W_{11} - W_{22})^2 + 4W_{12}^2})
\]

\[
\frac{1}{V_{slow}^2} = \frac{1}{2} (W_{11} + W_{22} + \sqrt{(W_{11} - W_{22})^2 + 4W_{12}^2})
\]

\[
\beta_z = \tan^{-1} \frac{W_{11} - W_{22} + \sqrt{(W_{11} - W_{22})^2 + 4W_{12}^2}}{2W_{12}}
\]

The azimuth of the fast velocity is 90° away from the azimuth of the slow velocities (Jenner, 2001).

For Dix-type interval ellipse coefficients, \( W_{i} \), we use the Grechka et. al., 1999 relation

\[
W^{-1} = \frac{T_0((l+1)-T_0(l-1))}{T_0(l)-T_0(l-1)}
\]

where \((l-1)\) is top layer, and \((l)\) is the bottom layer. Isotropic NMO velocities \( V_{NMO} \) and zero-offset traveltimes \( T_0 \) are used along with azimuthally variant time residuals, \( dT_{\phi} \) to estimate azimuthal traveltimes, \( T \), as follows:

\[
T = T_x + dT_{\phi}
\]

where

\[
T_x = \sqrt{T_0^2 + \frac{x^2}{V_{NMO}^2}}
\]

The azimuthally-variant residuals were auto-picked and applied to the COV gathers. Figure 3 shows the gathers before applying the residual traveltimes (left) and after applying them (right). A sequence of white and yellow backgrounds indicate offset. Offset changes occur where the background color changes. The Mahogany bench time picks from stacked data are indicated by light green on the prestack COV gather. It can be seen that the flatness of
Mahogany bench is significantly improved after the application residual travel times, especially at larger offsets. Another set of residuals were picked for the top of reservoir (Upper Green River formation) to calculate interval properties.

**Results**

VVAZ inversion has been performed in Matlab as described above to the part of the Mahogany Bench around the VSP. Fast RMS velocity, slow RMS velocity, and their directions were calculated. Figure 4 compares isotropic RMS velocity to fast and slow RMS velocities. Coordinates are with reference to the VSP borehole. From those three velocities, a velocity anisotropy percentage was calculated by dividing the difference between the fast and slow RMS velocities by the isotropic RMS velocity. Besides the method described above, VVAZ was performed in Hampson-Russell Suites, and the results are compared.

Figures 4, 5 and 6 compare the percentage and direction of anisotropy obtained by our code to Hampson-Russell software. We can see that anisotropy percentage obtained by both methods go up to less than 1.5%. Higher anisotropy zones, in both maps, are observed in northeast and southwest. In Figure 5, it can be seen that anisotropy orientation, obtained by methods, falls in the same quadrant. Figure 6 is a zoomed-in version of Figure 12 with selected area from Hampson-Russell’s and their corresponding area from our method. Arrows on left map from top to bottom have values of 40°, 19°, and 43° from x-axis.

![Figure 3. COV Gathers: Before (left) and after (right) applying azimuthal residuals.](image)

![Figure 4. Conventional isotropic RMS velocity (top) vs. VVAZ results (bottom): fast RMS velocity (bottom left) and slow RMS velocity. All values are in (1000 ft/s).](image)

![Figure 5. Comparison of anisotropy percentage obtained by two methods: Hampson-Russell’s software (left), VVAZ method described above.](image)

The interval anisotropy percentage is mostly 1 to 2%, but goes up to 5%. Those values are higher compared to the anisotropy percentage calculated for the base of the reservoir. The interval anisotropy orientation is mostly 63°. It falls in the same quadrant as the anisotropy direction,
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calculated for the base of the reservoir, that trends northwest to southeast.

Figure 6. Direction of VVAZ by two methods: Hampson-Russell’s software (left), VVAZ method described above at three selected zones (right).

Azimuthally-variant time residuals were picked for the top of the fractured reservoir, Upper Green River formation. Ellipse coefficients were inverted for. From the two sets of ellipse coefficients, a Dix-type interval coefficients were calculated as described by Equation (7). From those coefficients, fast, slow interval velocities, and their directions are calculated to estimate the interval velocity anisotropy intensity and orientation of the fractured reservoir, shown by Figure 7.

Conclusions

For the development of unconventional reservoirs, azimuthal variations of P-wave velocities can be a valuable tool for fracture information. In this paper, we have implemented an AVAz workflow with 3D pre-stack seismic data from Altamont-Bluebell field. Our target was the shallowest of the three targets of Uinta Basin, Upper Green River to Mahogany Bench. Maps of anisotropy intensity and direction were obtained and compared to maps that we obtained using Hampson-Russell Suites. Both direction and intensity maps correlate well in both models.

We think that the use of Dix-type interval coefficients has an advantage over the use of coefficients obtained from RMS velocities for a single layer because it makes VVAZ less sensitive to overburden properties.

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