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AVAZ and VVAZ practical analysis to estimate anisotropic properties

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Summary

Seismic anisotropic properties, such as orientation and intensity, play a key role in shale plays and fractured reservoir evaluation. A type of anisotropy often observed in shale plays is vertical transverse isotropy (VTI) because the layered shale is typically horizontal with vertical symmetry. Usually VTI can be estimated via higher-order NMO to correct for the layering effect. VTI also causes the AVO amplitude anomalies and then makes the practical application difficult for AVO attribute extraction and analysis.

Another type of anisotropy in fractured reservoir is horizontal transverse isotropy (HTI) because the reservoir usually is preferentially vertical aligned fractures. This type of anisotropy causes azimuthal amplitude and velocity variations which can become apparent in seismic azimuthal gathers.

According to seismic response to anisotropic signatures, there are two types of methods which can be used to study seismic HTI and VTI anisotropy. One method is seismic travel-time variations or velocity variations with azimuth (VVAZ) from seismic offset-gathers and another method is seismic amplitude variations from seismic azimuth-gathers (AVAZ).

In this paper two practical methods for HTI and VTI anisotropic media were studied respectively. For AVAZ, our methods separate seismic amplitude response into both isotropic and anisotropic contributions and then use seismic anisotropic part to infer anisotropic properties, and for traditional VVAZ, usually the top and bottom of horizons are needed and also there is poor vertical resolution. In order to achieve high resolution results, the seismic inverted velocity was integrated into the workflow to estimate the residual moveouts. One of VVAZ practical implementations is that our VVAZ method doesn't need to pick target top and bottom horizons.

In shale plays orthorhombic anisotropy is common and can be described by an orthorhombic velocity model or seismic amplitude approximating formula with Vertical Transverse Isotropy (VTI) and Horizontal Transverse Isotropy (HTI) models. An integrated method which will combine VVAZ and AVAZ methods was presented to study the anisotropic signatures in orthorhombic media or HTI/VTI media. The synthetic and real data examples have been tested and demonstrated positive results.

Seismic travel-time/velocity variations (VVAZ)

For a single orthorhombic layer model, the moveout for conventional P-waves can be approximated by the higher-order equation (Xu and Tsvankin, 2005):

$$t^2(X,\alpha) = t_0^2 + \frac{X^2}{V_{nmo}^2\,(a)} - \frac{2\eta_{effective}\,(a)X^4}{V_{nmo}^2\,(a)(t_0^2V_{nmo}^2\,(a)+(1+2\eta_{effective}\,)(a)X^2)} \quad (1)$$

where $t(X,\alpha)$ is the total travel time, t_0 is the zero-offset travel time, x is the source-receiver offset, $V_{nmo}\,(a)$ is the azimuth-dependent NMO velocity. The $\eta_{effective}\,(a)$ is the azimuth-dependent effective anisotropy parameters during orthorhombic media, but for pure VTI media, the $\eta_{effective}\,(a)$ is azimuth independent. In the formulation of Equation (1) for VTI media, the higher order parameter $\eta_{effective}$ describes the moveout component due to both vertical velocity heterogeneity and actual intrinsic VTI anisotropy.

For isotropic media:

$$t^2(X) = t_0^2 + \frac{X^2}{V_{nmo}^2} \qquad (2)$$

For pure HTI media: The near-offset variation in NMO velocity is obtained by setting $\eta_{effective} = 0$ and thus eliminating the third term in Equation (1). The HTI travel-time can be re-written:

$$t^2(X,\alpha) = t_0^2 + \frac{X^2}{V_{nmo}^2\,(a)} \qquad (3)$$

The different travel-time between HTI media and isotropic media:

$$\Delta t^2(X,\alpha) = t^2(X,\alpha) - t^2(X) = \frac{X^2}{V_{nmo}^2} - \frac{X^2}{V_{nmo}^2\,(a)}\ (4)$$

The residual moveout at the bottom of the fractured layer can be expressed as (Wang and Zheng, 2007):

$$\Delta t = -\frac{DV_0}{V_{rms}^2}\delta cos\theta sin^2\theta cos^2\varphi \qquad (5)$$

Where V_{rms} is the RMS velocity at the bottom of the fractured layer. V_0 is the interval velocity of the fractured layer along the direction of the fracture strike. δ is Thomsen's parameter of the fractured layer. θ is incident angle of seismic wave. φ is the azimuthal angle between seismic ray path and fracture strike direction. In order to achieve high resolution results, we utilize the seismic high-resolution inverted velocity to replace seismic interval velocity.

Given the redundant differential residual moveout pairs from the azimuthal gathers, one can infer the anisotropic parameters δ, which is the indicator of anisotropic intensity. Because of the ambiguity in the determination of fracture orientation using equation (5), the additional information is needed to make the correction. Fortunately, we can combine AVAZ method to study seismic amplitude azimuth variations to estimate the orientation and then apply the orientation to make the correction.

For pure VTI media, the offset normal moveout can be expressed without consideration of azimuthal variations:

$$\Delta t^2(X) = \frac{2\eta_{effective}\,X^4}{V_{nmo}^2\,(t_0^2V_{nmo}^2 + (1+2\eta_{effective})X^2)} \qquad (6)$$

And then anisotropic eta (η_{eff}) can be calculated:

$$\eta_{eff} = \frac{\Delta t^2 V_{nmo}^2\,(t_0^2V_{nmo}^2 + X^2)}{2X^2(X^2 - \Delta t^2 V_{nmo}^2)}\ (7)$$

Traditionally, Eta is related to the ratio of the vertical velocity and the horizontal velocity for each lithology. Because of the lithology intrinsic anisotropy, eta is also known to vary with the quartz and clay contents in conventional plays or anisotropy intensity in shale plays.

Seismic amplitude variations (AVAZ)

Amplitude-versus-Azimuth (AVAZ) has gained popular to extract fracture signatures, such as fracture intensity and the orientation from azimuth seismic data. The amplitude method using the Ruger's HTI media equation has been used to infer the fracture properties. Our synthetic example has demonstrated that AVAZ can be successfully applied for fracture detection, but in practical application the method is very sensitive to noise and the AVO effects compared with VVAZ methods.

For isotropic media, the seismic amplitude analysis can be performed by starting with Aki-Richard equation which was reformatted by Fatti as: (Hampson and Russell, 2013)

$$R^{ISO}(\theta) = \left(C_1 R_p + C_2 R_s + C_3 R_D\right) \text{ (8)}$$

Where $C_1 = 1 + tan^2(\theta)$, $C_2 = -8\gamma^2 sin^2(\theta)$, $C_3 = -\frac{1}{2} tan^2(\theta) + 2\gamma^2 sin^2(\theta)$, $\gamma = \frac{V_s}{V_p}$ and the P-reflectivity (R_p), S-reflectivity (R_s) and density reflectivity (R_D).

For the VTI media, the VTI can't causes the seismic amplitude azimuthal variations, but it is incident angle-dependent. The VTI anisotropic Fatti's formula can be re-written using the Ruger equation:

$$R^{VTI}(\theta) = \left(C_1 R_p + C_2 R_s + C_3 R_D\right) + C_4^v \Delta\delta + C_5^v \Delta\varepsilon + C_6^v \Delta\gamma \text{ (9)}$$

Where: $C_4^v = sin^2(\theta)/2$, $C_5^v = 0.5 sin^2(\theta) tan^2(\theta)$ and $C_6^v = \frac{4V_s^2}{V_p^2} sin^2(\theta)$. The three parameters $\delta, \varepsilon\ and\ \gamma$ are the Thomsen's anisotropic parameters.

For the HTI media, the seismic amplitude azimuthal variations can be described using the Ruger equation:

$$R^{HTI}(\theta, \varphi) = \left(C_1 R_p + C_2 R_s + C_3 R_D\right) + C_4 \Delta\delta^v + C_5 \Delta\varepsilon^v + C_6 \Delta\gamma \quad \text{(10)}$$

Where: $C_4 = 0.5(cos^2(\varphi) sin^2(\theta) + cos^2(\varphi) sin^2(\varphi) tan^2(\theta) sin^2(\theta))$, $C_5 = 0.5 cos^4(\varphi) sin^2(\theta) tan^2(\theta)$ and $C_6 = \frac{4V_s^2}{V_p^2} cos^2(\varphi) sin^2(\theta)$

For weak anisotropy: $\varepsilon^v \approx -\varepsilon$ and $\delta^v \approx \delta - 2\varepsilon$

For HTI+VTI media: seismic response equation can be described:

$$R^{HTI+VTI}(\theta, \varphi) = R^{ISO}(\theta) + R^{HTI}(\theta, \varphi) + R^{VTI}(\theta)$$

$$= \left(C_1 R_p + C_2 R_s + C_3 R_D\right) + (C_4 \Delta\delta^v + C_5 \Delta\varepsilon^v + C_6 \Delta\gamma) + (C_4^v \Delta\delta + C_5^v \Delta\varepsilon + C_6^v \Delta\gamma)$$

$$= R^{ISO}(\theta) + C_4^{hv} \Delta\delta + C_5^{hv} \Delta\varepsilon + C_6^{hv} \Delta\gamma \quad \text{(11)}$$

Where: $C_4^{hv} = C_4^v + C_4$, $C_5^{hv} = C_5^v - C_5 - 2C_4$ and $C_6^{hv} = C_6^v + C_6$

Case Examples

The real data and synthetic examples are applied for both methods. The figure 1(a, b) are two cdp anisotropic eta curves estimated from VTI moveout method. The positive and negative anomalies represent the different lithology contents. In this example, positive anomalies means the horizontal velocity is greater than the imaging velocity and implies high shale content and negative anomalies means that it is possible for carbonate environment.

Figure 2 is our synthetic model with two HTI shale play layers (2, 3), and four isotropic sand layers (1, 4, 5, 6). Seismic azimuth-gathers in 36 equal sectors with the incident angle from 0 to 45 degrees were generated to study the amplitude (velocity) vs. azimuth variations.

In CDP 100, the HTI anisotropy causes the amplitude azimuth-variations around the 1250 ms to 1360 ms from the larger angle gathers, which can be used to identify two anisotropic shale layers. For example, when the incident angle is greater than 30 degrees, the anisotropic amplitude anomalies are apparent. Because of the ambiguity of the azimuth from the velocity method, the amplitude azimuth variations method was applied to estimate the fracture orientation. The figure 3 is the inverted orientation results. The fracture orientation of left middle shale layer (2) is around 85 degrees and the orientation of left bottom shale layer (3) is around 130 degrees. The orientation results are consistent with the model parameters. Two methods also were applied to estimate the fracture intensity. Figure 4 is the results of fracture intensity, which were inferred from the velocity method (right) and amplitude azimuth method (left) respectively. The intensity also matches with the model. Based on the amplitude method, the Thomsen's three parameters can be inverted, but the velocity method can only estimate the Thomsen delta parameters.

The real data have been studied and the results are positive for identifying the fractured carbonate reservoir and shale plays.

Conclusions

In this paper we studied the anisotropic methods of both velocity and amplitude methods for the HTI and VTI media and presented both velocity and amplitude response equations for the HTI and VTI media respectively. In order to de-risk the ambiguity of orientation from the velocity method, the amplitude method can be used to correctly estimate the orientation of fracture. These two methods have demonstrated very similar results based on our synthetic data and real data. For the VTI media, the velocity method can also infer the anisotropic eta using the residual higher-order NMO moveout, which is the indicator for the lithology anomalies. For the HTI media, the azimuth-dependent gathers are necessary for the fracture detection. Moreover the amplitude method can also estimate the Thomsen's three parameters to support the anisotropic studies in details.

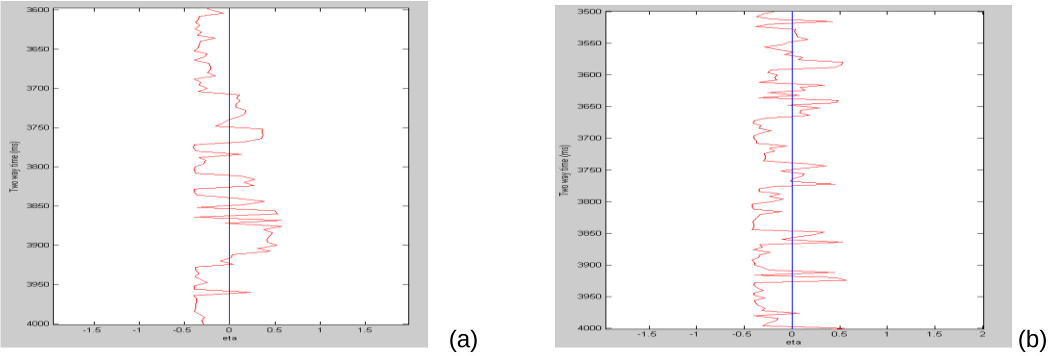

Figure 1: (a) and (b) are anisotropic eta curves estimated from two cdp gathers. In this example, compared with well logging lithology interpretation, eta < 0 means carbonate lithology and eta > 0 possible for shale anomalies

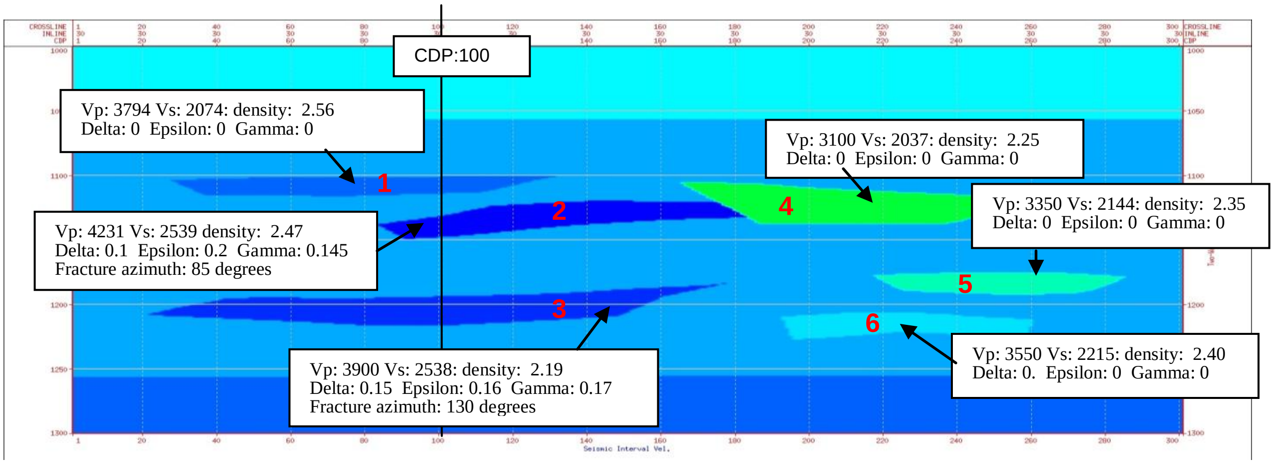

Figure 2: six sand/shale layers (No1-No.6) with different Vp, Vs and density. The left middle layer (No.2) is HTI anisotropic fracture with fracture direction 85 degrees, the left bottom layer (No.3) is HTI anisotropic fracture with fracture direction 130 degrees, and other four layers (No.1 and No.4-No.6) are isotropic.

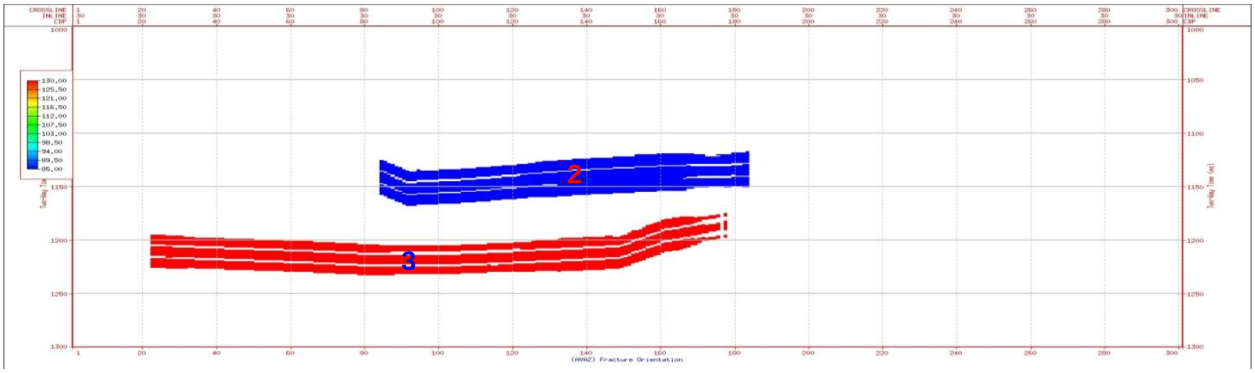

Figure 3: fracture orientation estimation based on seismic amplitude azimuth variation method. The left two anisotropic shale layers can be easily detected with fracture orientation (about 85 and 130 degrees) and the other four isotropic layers have no any facture signatures. Based on the amplitude azimuth variation method, the fracture orientation is unique and it doesn't need additional information to correct the fracture orientation.

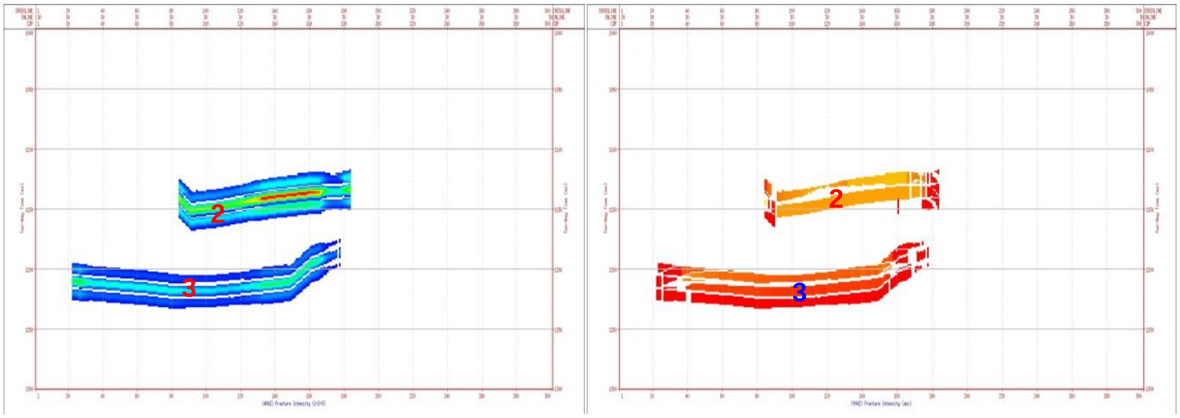

Figure 4: fracture intensity estimation of two shale layers from amplitude azimuth variation (left) and velocity method (right). The intensity of other four isotropic layers is near zero. Although the intensity magnitudes are different between two methods, they can easily identify the anisotropic layers from isotropic formation.

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