Azimuthal variation of velocity and moveout of PS converted waves in HTI media

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Summary

We focus on the moveout behavior of PS converted waves propagating in HTI media. Results from a synthetic seismic dataset show that the moveout of a PS converted wave is a cosine function of the angle between the azimuth of the raypath and the fracture direction. This implies that the NMO velocity of the PS converted wave is an ellipse. This result confirms theoretical analysis. The results also show that the azimuthal variation of PS converted waves is more significant than that of P waves, which demonstrates that analysis of PS waves to characterize fractures is more efficient than analysis of P waves. It provides an alternative procedure for determining fracture strike. Moreover, some other techniques developed for P waves can be similarly adapted to PS converted waves.

Introduction

Multi-component 3D seismic exploration has become increasingly important for detecting and characterizing fractured reservoirs. Fractures oriented in a preferred direction due to their stress history are one of the most plausible causes of horizontal transverse isotropy (HTI). Confident determination of fracture orientation significantly benefits the placement of horizontal and deviated wells.

Many seismic attributes (velocity, amplitude) have been studied to facilitate fracture characterization (Bakulin *et al.*, 2000, Li *et al.*, 2003, Vetri *et al.*, 2003, Dai, 2010). Specifically, the azimuthal variation of normal moveout (NMO) velocity is one of the useful attributes to characterize natural fractures. It has been proven that the variation of NMO velocity of pure-mode waves (P and S-wave) is elliptical in HTI media (Tsvankin, 1997), and this has been already applied to assess natural fractures. However, P-waves only show anisotropic effects in the far offset, while S-wave sources are quite expensive and not widely used, so PS converted waves should be considered as an alternative way. The variation of NMO velocity of PS converted waves in HTI media has been proven to be close to an ellipse (Liu *et al*., 2011). However an analysis of synthetic data used to confirm the elliptical variation of PS converted wave velocity has not so far been provided. Furthermore, the analysis of variation of moveout is not well studied. In this paper, we will fill these gaps by analyzing the moveout of PS converted waves of a synthetic seismic dataset produced by the reflectivity method (Taylor, 2001).

Theory

Azimuthal variation of PS wave NMO velocity in HTI media

In HTI media caused by aligned vertical fractures, the fracture strike is perpendicular to the symmetry axis. For shear waves, the fast S-wave propagates in the fracture direction while the slow S-wave propagates in the direction of the symmetry axis. Waves recorded in the horizontal radial component which are considered to be PS converted waves may be a combination of both fast and slow S-waves.

The PS converted wave measured in the horizontal radial component contains P and S-waves propagating at the same azimuth. Thus its NMO velocity is a combination of P and S-wave NMO velocities (Li and Yuan, 2003):

$$v_{ps2}^2(\theta) = \frac{1}{1+\gamma_0} v_{p2}^2(\theta) + \frac{\gamma_0}{1+\gamma_0} v_{s2}^2(\theta) \qquad (1)$$

where v_{ps2}, v_{p2} and v_{s2} are the NMO velocities of PS converted, P and S-waves, respectively. θ is the azimuthal angle between the vertical plane and fracture direction. Equation (1) is close to an ellipse if the condition of weak anisotropy is satisfied. This elliptical variation can be written as (*Liu et al*., 2011):

$$V_{ps2}^2(\theta) = \frac{v_{ps2-0^o}^2 v_{ps2-90^o}^2}{v_{ps2-0^o}^2 \sin^2\theta + v_{ps2-90^o}^2 \cos^2\theta} \qquad (2)$$

where v_{ps2-0^o} and v_{ps2-90^o} are the NMO velocities at θ =0^o (fracture strike) and θ =90^o (symmetry axis), respectively. Figure 1 shows an example of NMO velocities of PS converted, P and S-waves. The NMO velocity of the PS converted wave is calculated using Equation (1). In this example (v_{p2-0^o} =2000m/s, v_{s2-0^o} =1000m/s, v_{p2-90^o} =1400m/s, v_{s2-90^o} =800m/s) the vertical velocity ratio (γ_0) is set to be 2.2. The PS wave NMO velocity (middle solid curve) looks like an ellipse, but mathematically it is not.

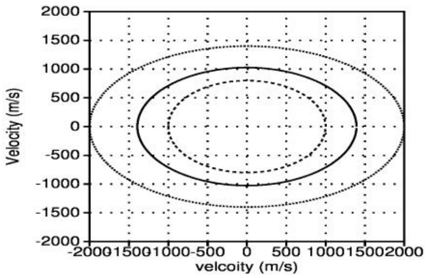

Figure 1. NMO velocities of P (outer dotted curve), PS converted (middle solid curve) and S (inner dashed curve) waves

Azimuthal variation of PS wave moveout in HTI media

The moveout equation of the PS converted wave is:

$$t_{ps}^2 = t_{ps0}^2 + \frac{x^2}{v_{ps2}^2} - 2\kappa_{eff} \frac{x^4}{v_{ps}^2 (t_{ps0}^2 v_{ps2}^2 + m x^2)} \quad (3)$$

Substituting Equation (2) into Equation (3) and ignoring the anisotropy term (the last term) for weak anisotropy, we have:

$$t_{ps}(\theta) \approx \sqrt{t_{ps0}^2 + x^2 [\frac{\sin^2(\theta)}{v_{ps2-90^o}^2} + \frac{\cos^2(\theta)}{v_{ps2-0^o}^2}]} \quad (4)$$

Equation (4) can be approximated into:

$$t_{ps}(\theta) \approx (C + \frac{A}{4C}) + \frac{A}{4C}\cos 2\theta \quad (5)$$

$$A = x^2 v_{ps2-90^o}^2 (v_{ps2-0^o}^2 - v_{ps2-90^o}^2) \quad (6)$$

$$C = \sqrt{t_{ps0}^2 + x^2 v_{ps2-90^o}^2} \quad (7)$$

Therefore the azimuthal variation of the moveout of the PS converted wave is close to a cosine function, which provides another way to confirm the elliptical variation of PS converted wave velocity.

Synthetic data

The synthetic data is produced by the reflectivity method (Taylor, 2001). The model and parameters are displayed in Figure 2. The second layer is an HTI layer induced by vertical fractures. The fracture strike is at azimuth 90^o in the horizontal plane (Figure 3).

Figure 4a shows the PS converted wave events (offset 600m). Figure 5a is an enlarged part of the event at about 3s in Figure 4a. Figure 4b shows the P wave events and Figure 5b is the enlargement of the target event (at 1.48s). The azimuthal variation of the PS converted wave in Figure 5a is more significant than that of the P wave in Figure 5b, which demonstrates that analyzing PS waves to characterize fractures is more efficient than using P waves, in the middle offset. In Figure 5a, it can be seen that the PS converted wave propagates fast in the direction of fracture strike and propagates slowly in the direction of symmetry axis. In other directions, a PS converted wave contains both slow and fast S-waves. This phenomenon shows that it is possible to recover the velocity variation of PS converted waves in HTI media.

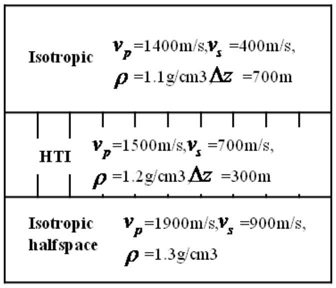

Figure 2. Model details

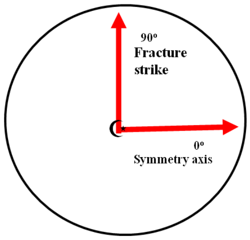

Figure 3. Fracture strike

In order to analyze the moveout variation of PS converted waves, time-value picking of the target event (Figure 5a) is applied. Due to the influence of both the fast and slow S wave, the waveform is distorted to some extent. Therefore it is difficult to obtain an accurate value. Firstly, the top edge and bottom edge of the peak of each azimuth are picked. Secondly, the average time value of the peak is calculated. Finally, those time values are fitted separately into cosine functions. Figure 6 and 7 are the results of fitting the time values picked from the top and bottom edges, respectively. The cosine function fitted by the average values is shown in Figure 8. In all three figures, the solid red curves are the fitted cosine curves while the black dashed curves are the picked values. In Figure 6 and 7, the variation is similar to the cosine function but some deviations can be noticed. In Figure 8, the differences between the average values and fitted cosine function are not significant. Therefore the analysis of azimuth variation of the moveout of PS wave is in accordance with the derived Equation (5). It confirms that the velocity variation of the PS wave NMO velocity is close to an ellipse.

Then conventional velocity analysis is performed to acquire the real velocity variation of the PS converted wave. The event at about 3s is given priority, due to it showing the azimuthal variation. First, the NMO velocities of the PS wave at about 3s along the fracture strike and symmetry axis are obtained. The relative difference between the maximum and minimum NMO velocity is about 3.4%, which satisfies the condition of weak anisotropy. Secondly the NMO velocities at other azimuths (30^o, 60^o, 120^o, 150^o, 180^o, 210^o, 240^o, 270^o, 300^o, 330^o) are obtained by the same velocity analysis. Figure 9 shows the comparison of the real velocity variation and the calculated velocity variation. The solid black curve is the velocity ellipse calculated by Equation (2). The red stars are the values of NMO velocities acquired from the real velocity analysis. In Figure 9, the real values are close to the ellipse although there are some insignificant differences. Therefore the analysis of the synthetic data confirms that the NMO velocity of PS converted wave in HTI media is close to an ellipse in the condition of weak anisotropy.

Conclusions

In this paper, we have studied the azimuthal variation of PS converted waves in HTI media. A cosine function is derived for the azimuthal variation of the moveout of the PS converted wave measured in the radial component. By analyzing the synthetic data, the moveout variation of the PS converted wave is found to be close to the fitted cosine function and the NMO velocity of the PS converted wave is close to an ellipse. The azimuthal variation of PS converted waves is more significant than that of P waves, which demonstrates that analyzing PS waves to characterize fractures is more efficient than analyzing P waves. Therefore PS converted waves provide an alternative way to detect and characterize natural fractures. Moreover, some techniques developed for P waves can be similarly adapted to PS converted waves.

Acknowledgements

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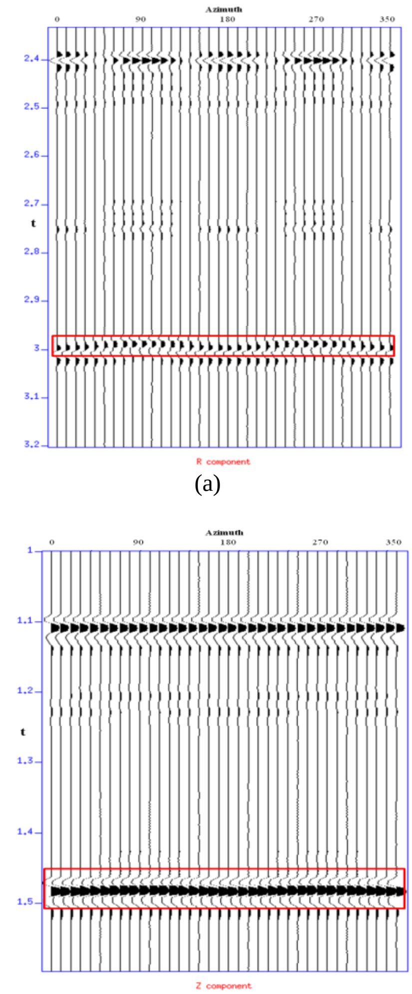
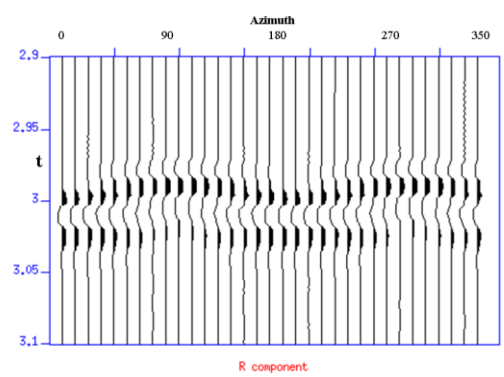
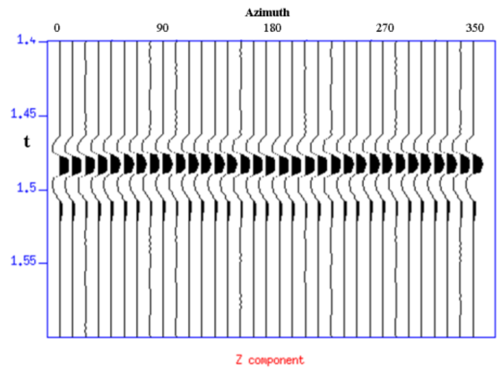


Figure 4. The azimuthal gathers of radial (a) and vertical (b) component.



(a)

Azimuthal variation of PS converted wave in HTI media



(b)

Figure 5. The enlarged parts of the red rectangles in Figure 4a and 4b, respectively.

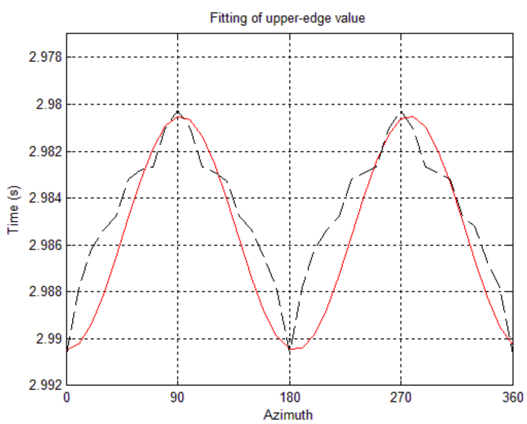


Figure 6. Fitting result of values from the top edge

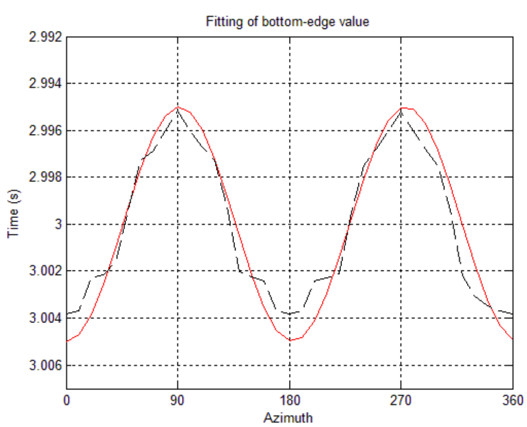


Figure 7. Fitting result of values from the bottom edge

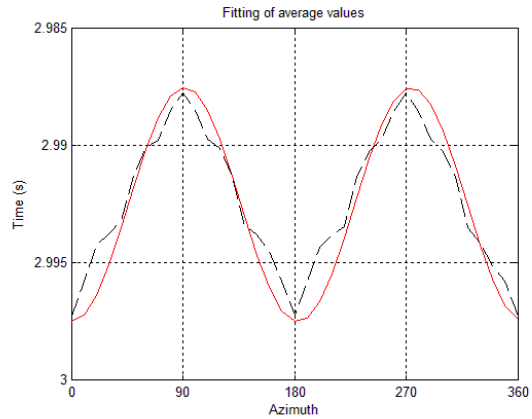


Figure 8. Fitting result of the average values

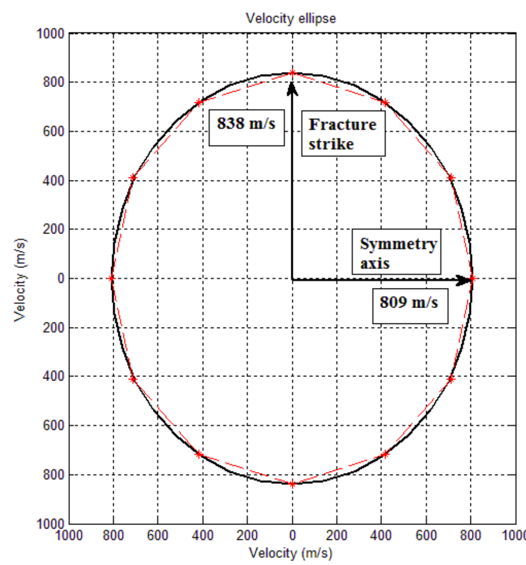


Figure 9. Velocity ellipse
(The solid black ellipse is calculated by Equation 2, the red stars are the NMO velocities obtained by the conventional velocity analysis)