The ODR-dependent attribute analysis of HTI media based on full azimuthal gather: A synthetic study

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Summary

The vertical aligned fractures are observed in the tight sandstone gas reservoir formation in Sichuan Basin, southwest China. They contribute to the permeability of the reservoir, and also result in the azimuthal anisotropy of seismic responses. PS-waves show a wider applicable offset range and a larger observable azimuthal anisotropy than PP-waves, and bottom PP-and PS-waves are less dependent on the offset than top PP- and PS-waves for fracture layer, respectively. The long axis of PP-wave fitted ellipse analysis, at near- and far-offset corresponds to fracture normal and strike, respectively, which shows a contrary result. However, unlike in PP-wave elliptical analysis, no matter near- or far-offset, the long axis of PS-wave always point to a single direction (strike for water-saturated and normal for dry fracture), which can used to better analyze azimuthal anisotropy. So, offset range must be taken into account for picking amplitude of seismic data and elliptical analysis and the combination of the elliptic analysis of PP- and PS-waves can accurately determine the information of the fracture strike and density.

Introduction

In this study, we build a realistic geologic model based on real well-logging data using the effective medium theory. Then, the elastic seismograms are generated and the azimuthal variation of PP and PS-converted wave reflections are analysed for the top and the bottom of the fractured formation. Similar synthetic studies are performed for the Bakken formation by Ye et al. (2010) and Qian et al. (2007, 2012) using only PP-wave responses for the top reflection of the fractured formation. This study involves in the PS-converted wave to analyse the AVO response for both top and bottom reflections. We study the effect of offset-depth ratio (ODR) on the feasibility of performing elliptical anisotropy analysis on azimuthal PP- and PS-wave data, with the aim of using the modelling results as guidance in real seismic data application.

Azimuthal seismic modeling

Well-logs in Figure 1a illustrate the fractured layers of Upper Triassic formation (TX2) in Sichuan Basin. TX2 is the deposit of sand-mud alternative delta facies at depth from 4500 to 5300m. This formation consists of a group of gas-bearing tight sand layers. The target layer has stronger impedance than the surrounding layers. Imaging logging indicates the presence of vertical aligned fractures. We build a three-layered model (Figure 1b) to generate synthetic three-component data, which represents a typical tight-gas reservoir that has a bigger velocity than overburden and low/high impedance contrast. The top layer of the model is isotropic with a PP-wave velocity of 4700m/s. The middle layer of the model is an HTI medium, which simulates vertically aligned fractures in an isotropic medium using Hudson theory. The bottom layer represents isotropic half-space (Figure 1b). The parameters of model and fracture and infill different fluids are showed in Table 1, 2, 3, respectively. We set the fracture density as 0.1and the azimuth of the fracture strike in the layer is 90° (Figure 1b).

![Figure 1](image)

<table>
<thead>
<tr>
<th>Layer</th>
<th>Density</th>
<th>Vp(km/s)</th>
<th>Vs(km/s)</th>
<th>H(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overburden</td>
<td>2.6</td>
<td>4.7</td>
<td>2.5</td>
<td>500</td>
</tr>
<tr>
<td>Reservoir</td>
<td>2.7</td>
<td>5.52</td>
<td>2.9</td>
<td>300</td>
</tr>
<tr>
<td>Halfspace</td>
<td>2.8</td>
<td>6</td>
<td>3.15</td>
<td>∞</td>
</tr>
</tbody>
</table>

Table 2: Parameters of crack and fluid
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<table>
<thead>
<tr>
<th>Density Aspect ratio</th>
<th>Radius(m)</th>
<th>Bulk modulus (GPa)</th>
<th>Shear modulus (GPa)</th>
<th>Fluid density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.001</td>
<td>2.25</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3: Parameters of infill different fluids

Fluid type | Density (g/cm³) | Bulk modulus (GPa)
---|-----------------|-------------------
gas | 0.001 | 0.4
oil | 0.8 | 0.8
water | 1 | 2.25

A 1500m spread with a 30m receiver interval for extending the ODR to 3 is used to construct full-wave synthetic datasets (Figure 2) using the ANISEIS package based on the reflectivity method (Taylor, 1996). The azimuth coverage is from 0° to 360° every 2° degree interval. Both dry and water-saturated are considered. When the observed azimuth is perpendicular and parallel to the fracture strike, the T-component is zero, but seismic waves propagate at an intermediate angle away from the fracture strike, the shear-wave will split into a fast S-wave (S₁) that propagates parallel to fracture strike and a slow S-wave (S₂) that propagates normal to fracture strike.

In Figure 2, the labels Pp and Pbpp in the panels represent the P-waves reflected from the top and bottom of the fracture layer, respectively, and Ps and PPs represent the PS-converted wave from the top and bottom of the fracture layer. T-components at 0° and 90° azimuths equal zero, however T-components is not 0 at 30° and 60° azimuths, which exposes shear-wave splitting.

For a given offset, we can get an azimuthal-sector gather (Figure 3 & 4), we can see obvious azimuthal anisotropy especially for the bottom reflection of fracture layer. T-component both at the top and bottom of the fractured layer show an obvious azimuthal dependence with zero-crossings and amplitude polarity reversals. The moveout of bottom reflected Pbpp-wave has an obvious sinusoidal variation with the increase of the offset (ODR≥1) due to the influence of fracture (Figure 4).

Considering the model we build, the max incidence angle can reach 56.3° (just estimated by the straight ray trace and the critical angle for overburden and fracture layer is 58.4°), so the reflectivity cannot turn to the complex value. The incidence angle is 45° (ODR=1) and ODR=1.5 (offset=750m) both has not clear polar reversals for Pp-wave, however when the ODR≥2.0, the obvious polar reversal also occurs for the top reflected Pp-wave (black rectangle in Figure 3c&d), but when the fracture is saturated with water, the reversal do not exist (Figure 4). I think the reason is that when the offset is much more than depth, the converted wave energy will largely enhance which will has a non-negligible effect on the amplitude of PP-wave and the time delay will increase.

In Figure 5, for PS-wave in R-component from bottom reflection, the azimuthal anisotropy has been shown when the offset is small (ODR≤1). So, PS-wave has little offset-dependence for elliptical anisotropy analysis.
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Table 4: the relationship between top and bottom reflection depth and offset

<table>
<thead>
<tr>
<th>Offset</th>
<th>150m</th>
<th>250m</th>
<th>500m</th>
<th>750m</th>
<th>1000m</th>
<th>1250m</th>
<th>1500m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offset</td>
<td>0.5</td>
<td>0.5</td>
<td>1.0</td>
<td>1.5</td>
<td>2.0</td>
<td>2.5</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Table 5: the relationship between top and bottom reflection depth and offset

<table>
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<tr>
<th>Offset</th>
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<th>1500m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offset</td>
<td>0.5</td>
<td>0.5</td>
<td>1.0</td>
<td>1.5</td>
<td>2.0</td>
<td>2.5</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Figure 3: Azimuthal gather of PP-wave with different offsets (a) 150m, (b) 700m, (c) 1250m, (d) 1500m

Figure 4: Azimuthal gather of PP-wave with different offsets (a) 150m, (b) 700m, (c) 1250m, (d) 1500m

Figure 5: Azimuthal gather of PS-wave with different offsets (a) 150m, (b) 250m, (c) 500m, (d) 750m

T-component shows that apparent zero-crossings and polarity reversals emerges periodically (Figure 6a), which has a zero-dependence on offset. Given the small offset (ODR≤1), the maximum amplitude corresponds to the direction of 45° away from the fracture strike (black dashed line Figure 6b), or secondary maximum refers to the direction of 45° away from the fracture normal, but there is a certain deviation in the large offset. This point can indicate the fracture distribution information.

Figure 6: (a) The Azimuthal gather of PS-wave in T-component (red arrow represents fracture normal and white arrow represents fracture strike). (b) normalized amplitude variation with offset and azimuth. (c) Another way to display of (b) and negative amplitude values has been taken the absolute value for better symmetric comparison.

Given the fixed offset at different offset-depth ratios, we pick the azimuthal amplitude of Pp, Ppp, Ps and PPss-wave for fracture layer (Figure 7 & 8) in the case of water-saturated and dry fracture. For the elliptical analysis of Pp-wave under water-saturated fracture, the ideal offset range is ODR≤1, and the long axis corresponds to fracture normal, for 1≤ODR≤1.5, the distinction between long and short axis is ambiguous. When the ODR≥2.0, the long axis refers to fracture strike.

However, the elliptical long axis of PS-wave’s amplitudes at near-offset and far-offset both correspond to fracture strike, which has an opposite result on fracture direction compared with dry fracture. For Ppp-wave, the ideal offset is ODR≤1 for water-saturated fracture and the long axis refers to fracture normal. But for dry fracture, the offset has a wider range and long axis represents fracture normal.

The energy of PS-wave increases first and then decreases when the offset is close to the depth of fracture layer, so we can choose the near- or far-offset instead of middle offset, and no matter near- or far-offset, the long axis always point to single direction/strike for water-saturated and normal for dry fracture) compared with Pp. However, the azimuthal amplitude distribution looks like a ‘peanut’, but can still be fit to an ellipse with its major axis in the direction of fracture strike or normal.
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![Figure 7](image1.png)  
**Figure 7:** (a) The AVOA for Pp-wave, (b) The AVOA for PPpp-wave, (c) The AVOA for Ps-wave, (d) The AVOA for PPss-wave. Here, AVOA represents amplitude versus offset and azimuth.

![Figure 8](image2.png)  
**Figure 8:** (a) The AVOA for Pp-wave, (b) The AVOA for PPpp-wave, (c) The AVOA for Ps-wave, (d) The AVOA for PPss-wave. Here, AVOA represents amplitude versus offset and azimuth.

Similarly, the travel time of PPpp-wave also shows offset-dependence and obvious azimuthal variation can seen at far offset, which is ideal for elliptical fitting. Both Pp- and Ps-waves are not suited to elliptical fitting, even at far offset. PPss-wave can show obvious sinusoidal variation or ellipse in polar coordinate system at small offset (Figure 9), however, at far offset, the curves are no longer regular sine.

![Figure 9](image3.png)  
**Figure 9:** (a) The TVOA for Pp-wave, (b) The TVOA for PPpp-wave, (c) The TVOA for Ps-wave, (d) The TVOA for PPss-wave. (The color code of offset is same with Figure 7&8). Here, TVOA represents travel time versus offset and azimuth.

**Conclusions**

Ps&PPss-waves show a wider applicable offset range and a larger observable azimuthal anisotropy than Pp&PPpp-waves, and PPpp-and PPss-waves are less dependent on the offset than Pp- and Ps-waves for fracture layer, respectively. The dependence of offset is not the same with and without fluid. Unlike in P-wave elliptical analysis, no matter near- or far-offset, the long axis of Ps-wave always point to a single direction (strike for water-saturated and normal for dry fracture), which can used to better analyze azimuthal anisotropy. So, offset range must be taken into account for elliptical analysis and the combination of the elliptic analysis of PP- and PS-waves can accurately determine the information of the fracture strike. Further studies should consider the effects of saturation and layer thickness.

**Acknowledgements**

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