Azimuthal variations of PP- and PS-wave attributes: a synthetic study

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Summary

We present an azimuthal anisotropy analysis with synthetic wide azimuth multi-component data in the presence of vertically aligned fractures. The analysis of azimuthal P-wave amplitudes reveals that, though the data of near offset are suitable for elliptical anisotropy analysis, the data of very small offset do not show significant azimuthal variations, and the optimal data suitable for ellipse fitting may be limited to the those with offset-depth ratios of between 0.3 and 1.0. Azimuthal interval travel-time analysis is more suitable for data with large offset, because big azimuthal interval travel-time variations can only develop in data with large offset. Both amplitudes and interval travel-time of radial component of PS-wave may also be used to obtain fracture information through elliptical anisotropy analysis. The azimuthal amplitude variations of radial component of PS-wave show clearer elliptical distribution than that of P-wave, and the long axis of fitted ellipse indicates fracture normal. The overall offset range of PS-wave data suitable for azimuthal amplitude analysis is wider than that of P-wave. The azimuthal interval travel-time of radial component displays more obvious elliptical distribution than that of P-wave.

Introduction

The use of seismic anisotropy to characterize natural fractured reservoirs started in the 1980's, and the underlying physics for this technology comes from the equivalent medium theory for seismic wave propagation in fractured media, which has been intensively studied by many authors (e.g. Hudson, 1981; Liu et al, 2000) According to these theories, a medium containing vertically aligned fractures with scale length much less than the wavelength can be modelled by an equivalent azimuthally anisotropic medium for seismic wave propagation. Numerical modelling based on the equivalent medium theories reveals that azimuthal variations in P-wave amplitudes and travel-time can be used to characterise fractured medium and this has become standard practice. It is widely believed that in this practice a good azimuth-offset distribution is essential. A 3D physical modelling example of azimuthal P-wave analysis reveals that different data attributes may require different offset distribution to obtain optimal results (Wang et al, 2007).

Shear-wave splitting can be an effective way to obtain fracture information (Li, 1997). Yet, with the development of data acquisition techniques, more and more 3D multi-component data with wide azimuth-offset distribution have become available, which provide not only wide azimuth P-wave data, but also wide azimuth PS-wave data. Do the attributes of PS-waves also show elliptical distribution with azimuth just like that we have seen in azimuthal P-wave analysis and can be used to infer fracture information? If so, it will provide additional opportunities to obtain fracture information and the reliability of final fracture characterisation results will be improved when we do a combined azimuthal analysis with azimuthal P-wave and PS-wave data.

Model and synthetic data

The model we used to generate synthetic multi-component data is shown in Figure 1a, which is a simple three-layer model so that we can get the answers more directly. The top layer of the model is isotropic, and the middle layer is a

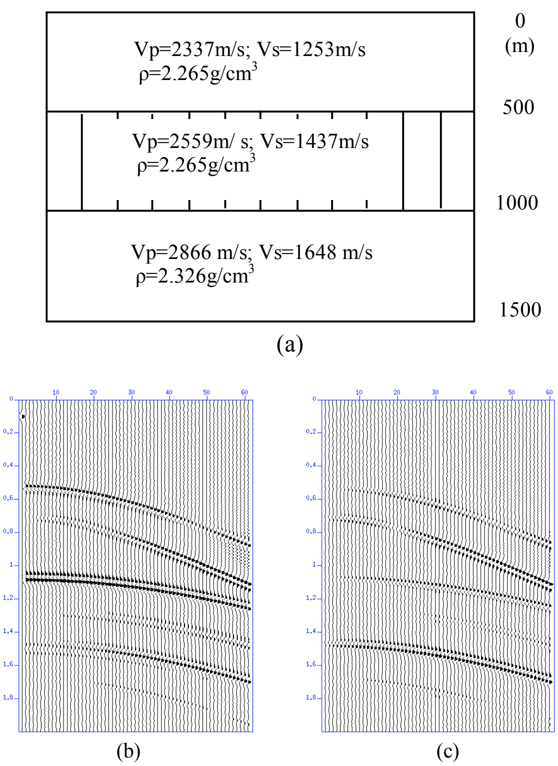

Figure 1: Model and synthetic data in source gather.
(a) model; (b) P-wave; (c) Radial component of PS-waves.

simulated HTI media with vertical aligned fractures in an isotropic medium. The fractures are simulated with aligned cracks of penny shape in planar distribution (Liu et al, 2000), and the aspect ratio and radius are 0.01 and 0.1, respectively. In order to study the efforts of fracture density in azimuthal seismic response, the fracture density is assigned with 0.1 and 0.18 separately. The azimuth of fracture strike in the layer is 0^o. The material in cracks is assumed to be fluid with P-wave velocity of 1200m/s and density of $0.95 g/cm^3$. The bottom layer is an isotropic medium.

Figure 1b and 1c show a synthetic data example based on the model. Notice the first trace in Figure 1b denotes the source wavelet. The offsets of the data range from 25m to 1500m, indicating the straight ray-path incident angles ranging from 0^o to 37^o for the reflections at the bottom of the fracture layer. Since the ray-paths normally are not straight in practice, it will be easier for us to use offset-depth ratio to represent incident angle. The azimuth of the synthetic data ranges from 0^o to 360^o and the azimuth sampling interval is 10^o.

Effects of offset coverage on P-wave

Though the P-wave amplitudes of near offset may be used for elliptical anisotropy analysis, how to choose appropriate offset still remains not so clear. Figure 2a shows the azimuthal variations of P-wave amplitudes at the top of the fracture layer with different offsets. It is obvious that only the amplitudes with offset-depth ratio less than 1.0 are suitable for ellipse fitting. When offset-depth ratio is bigger than 1.0, the fitted ellipses may give contradictory information. However, it also shows that the ellipse fitted with amplitudes of very small offset (e.g., offset-depth ratio is 0.2) is quite close to a circle, which means the azimuthal amplitude variations at small offsets are very small. In real data analysis, where noise problem is often involved, the azimuthal amplitude variations at very small offset will become even more ambiguous. In this case, the optimal offset-depth ratio for ellipse fitting with amplitudes is between 0.6 and 1.0. The long axes of fitted ellipses indicate fracture strike.

When interval travel-time is used for ellipse fitting, the effect of offset coverage is the opposite. Azimuthal variations of interval travel-time can only be observed in data with sufficiently large offset. If the offset-depth ratio is less than 1.0 in this model (Figure 3a), the azimuthal variations of travel-time are almost ignorable.

Figure 4 and Figure 5 show that, for a fixed offset, the ratio of long axis to short axis of the ellipse fitted with P-wave amplitudes (Figure 4d, 4e, 4f) or travel-time (Figure 5d, 5e, 5f) may be used to infer fracture density. However, the value of axis ratio may vary with offset (Figure 2, Figure 3) and need to be calibrated when a wide range of offsets are applied to estimate fracture density.

Elliptical analysis of PS-waves

Figure 2b shows that azimuthal amplitudes of radial component of PS-wave at the top of the fractured layer also display elliptical distribution with azimuth, which is similar to the behaviors of azimuthal P-wave amplitudes. For the same offset, the amplitudes of radial component vary more dramatically with azimuth than those of the P-wave, and the data suitable for ellipse fitting are those with offset-depth ratio ranging from 0.1 to 2.0, which means more offsets of radial component data can be included for elliptical anisotropy analysis compared to the P-wave data. In contrast to the results from P-wave data where the long axes of ellipses fitted with azimuthal amplitudes indicate fracture strike for this model, the long axes of the ellipses fitted with the amplitudes of radial component indicate fracture normal.

Figure 2c shows the azimuthal amplitude variations of the transverse component of the PS-wave data and the variations reveal zero-crossings and polarity reversals, which can also be used to infer fracture information (Li, 1998).

Figure 3b reveals that the interval travel-time of radial component of the PS-wave data within the fracture layer displays elliptical distribution with azimuth and the long axis of the ellipse indicates fracture normal, which is consistent with that from azimuthal P-wave analysis. It also requires sufficiently large offset to allow azimuthal variations of interval travel-time to develop significantly.

At a fixed offset, the ratio of long axis to short axis of the ellipse fitted with amplitudes (Figure 4a, 4b, 4c) or interval travel-time (Figure 5a, 5b, 5c) may increase with fracture density, which means the value of the axis ratio may be used to infer fracture density.

Discussion and Conclusions

We have carried out an azimuthal anisotropy analysis with the synthetic multi-component data. The azimuthal amplitude analysis of P-wave data reveals that the data suitable for elliptical anisotropy analysis are limited to those with offset-depth ratio of between 0.3 and 1.0. Thus, when we apply P-wave amplitudes for elliptical anisotropy analysis, we should focus on the data within this offset range. Since significant azimuthal interval travel-time variations only develop in the data with offset-depth ratio larger than 1.0, we may need to pay more attention to the far-offset data when we use interval travel-time for elliptical anisotropy analysis.

The analysis of azimuthal PS-wave data reveals that both the amplitudes and interval travel-time of radial component can be used to infer fracture information through ellipse fitting. The azimuthal amplitudes of the radial component of PS-waves at the top of fracture layer display clearer elliptical variations than that of the P-wave and the offset range suitable for azimuthal amplitude analysis is also larger. The long axis of ellipse fitted with the amplitudes of radial component indicates fracture normal for this model. The azimuthal interval travel-time of radial component of PS-waves also displays elliptical distribution and may be used to infer fracture information through elliptical anisotropy analysis.

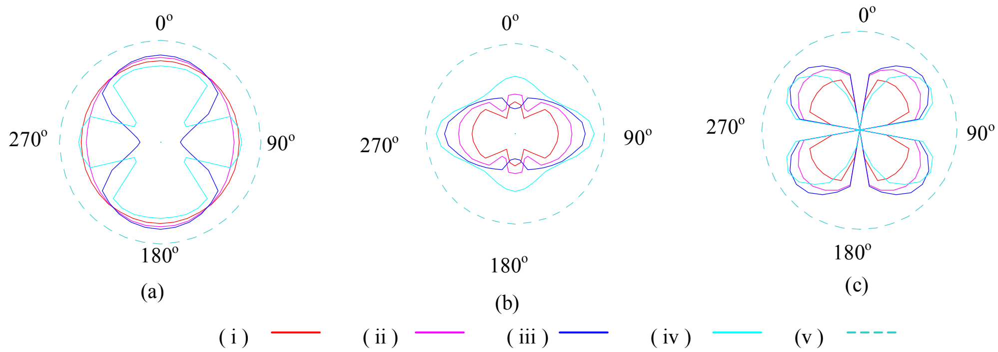

Figure 2: Azimuthal amplitude variations at the top of the fractured layer.
(a) P-wave; (b) R-component (PS-waves); (c) T-component (PS waves). The color curves (i) to (iv) represent offset-depth ratios of 0.2, 0.6, 1.0, 2.0, respectively. The curve (v) represents reference circle.

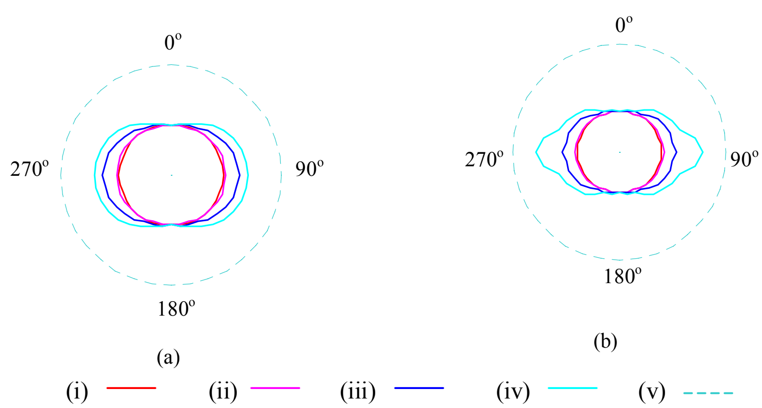

Figure 3: Azimuthal travel-time variations at the bottom of the fractured layer.
(a) P-wave; (b) R-component (PS-waves). The color curves (i) to (iv) represent the offset-depth ratios of 0.3, 0.5, 1.0, 1.5, respectively. The color curve (v) represents reference circle.

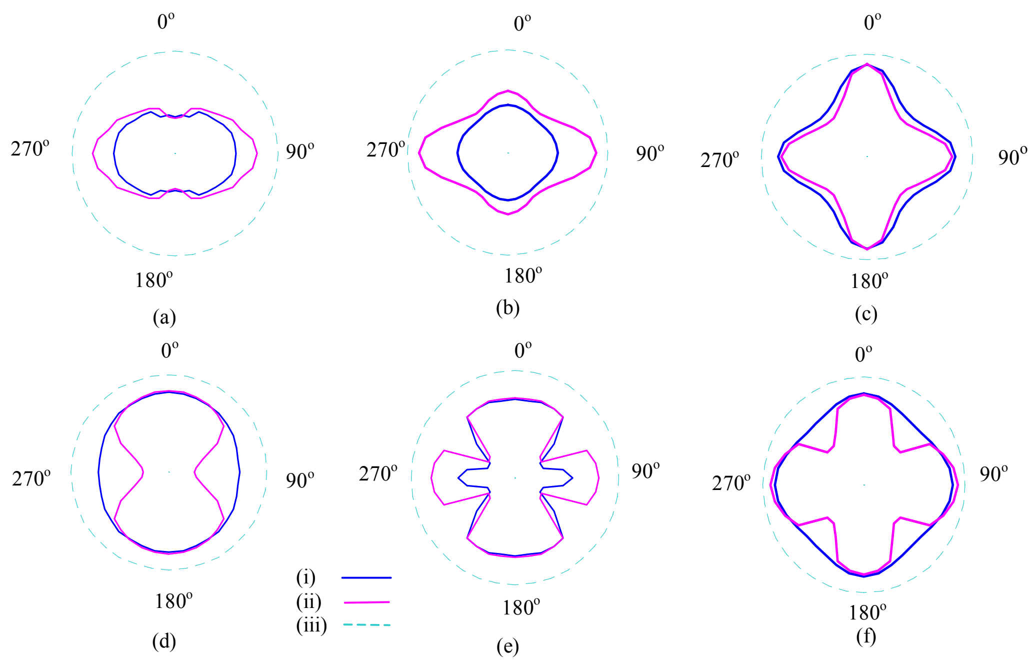

Figure 4: Azimuthal variations of amplitudes at the top of the fractured layer, with different fracture densities. (a), (b) and (c) are from PS-waves (R-compnent), with the offset to depth ratios of 1.0, 2.0 and 3.0, respectively; (d), (e) and (f) are from P-wave. (i) and (ii) represent fracture densities of 0.1 and 0.18, and (iii) represents reference circle.

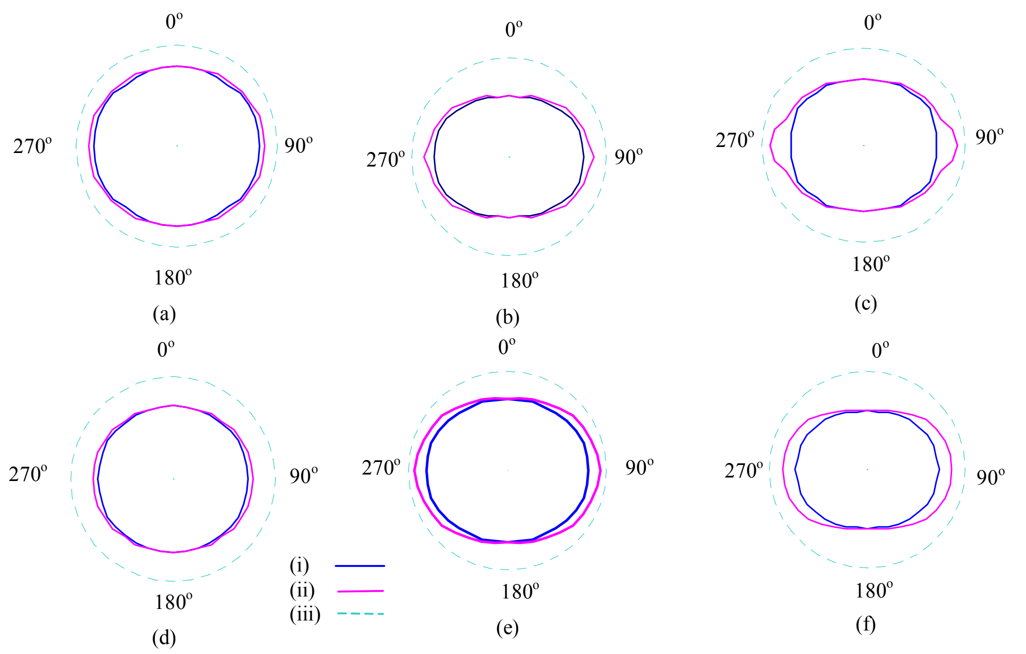

Figure 5: Azimuthal variations of travel-time at the bottom of the fractured layer, with different fracture densities. (a), (b) and (c) are from PS-waves (R-compnent), with offset to depth ratios of 0.5, 1.0 and 1.5, respectively; (d), (e) and (f) are from P-wave. (i) and (ii) represent fracture densities of 0.1 and 0.18, and (iii) represents reference circle.