Fracture characterization with azimuthal attribute analysis of PS-wave data: modelling and application
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Summary
We carry out azimuthal seismic anisotropy analysis of P- and PS-wave for fracture characterization with numerical modelling and a 3D3C dataset. Numerical results reveal that both the amplitudes and interval travel-time of the R-component of PS-wave can be used to infer fracture properties through ellipse fitting as that in azimuthal P-wave attribute analysis. In the real 3D3C data analysis, the fracture properties obtained from the azimuthal R-component analysis of the PS-wave data agrees with that inferred from the geological and logging information.
Introduction

Fractured reservoirs are common worldwide and fracture characterization plays an important part in reservoir development. The use of seismic anisotropy to characterize fractured reservoirs started in the 1980’s and has been gradually gaining the acceptance of the hydrocarbon industry. The underline physics for this technology comes from the equivalent medium theory for seismic wave propagation in fractured media, which has been intensively studied by a range of authors (e.g. Hudson, 1981; Liu et al, 2000; Chapman, 2003; amongst others.). According to these theories, a medium containing vertically aligned fractures with scale length much less than the wavelength can be modeled by an equivalent azimuthally anisotropic medium for seismic wave propagation. Numerical modelling based on the equivalent medium theories reveals shear-wave splitting and azimuthal P-wave amplitude and travel-time variations as diagnostic features for fractured media. A 3D physical modelling example of azimuthal P-wave analysis also reveals different seismic attributes may have different requirements to obtain optimal results (Wang et al, 2007).

With the development of data acquisition techniques and the interest of use PS-wave to characterize fracture properties in fractured reservoirs, more and more 3D multi-component seismic data with wide azimuth-offset coverage have become available, which provide not only wide azimuth P-wave data, but also wide azimuth PS-wave data. If the azimuthal attributes of PS-waves also show similar azimuthal anisotropy features like that of P-wave, we may use the similar techniques applied on P-wave data to infer fracture properties with PS-wave data. Then with a combined analysis of the fracture information obtained from azimuthal P-wave and PS-waves analysis, the overall reliability of fracture characterization results can be improved.

In this paper, we first carry out azimuthal anisotropy analysis for azimuthal PS-wave based on HTI medium for fracture characterization through numerical modelling, then apply the method on a wide-azimuth 3D3C dataset acquired on a fractured reservoir.

Numerical modelling

The model and parameters are displayed in Figure 1a, the middle layer is a HTI medium. The modelling azimuth ranges from 0° to 360° and the azimuth sampling interval is 10°. The colour of the curves in figure 1 represents the results come from different fracture densities: the red represents the fracture density of 18%, while the blue represents the fracture density of 10%. The offset is set as 500m for amplitude modelling and 1000m for interval travel-time modeling so that the depth to offset ratio at the reflection point is always 1.0. Since seismic ray paths are not straight lines, it is difficult to know the angle of incidence at analysis points. Thus it is more convenient to use the depth to offset ratio than use the angle of incidence.

We first carry out numerical modelling for azimuthal P-wave anisotropy analysis for comparison. Figure 1b shows the azimuthal amplitude distribution at the top interface of the HTI layer and figure 1c shows the azimuthal interval travel-time distribution within HTI layer. It reveals that both the amplitudes and the interval travel-time are in elliptical distribution with azimuth, the long axis of the ellipse is in fracture strike direction for amplitude attribute and in fracture normal direction for interval travel-time attribute, and the long to short axis ratio is related with fracture density. However, the modelling results also reveal that not all data are suitable for elliptical fitting to obtain fracture information, the azimuthal attributes of data with very small offset and very large offset do not appear in elliptical distributions. Thus the usable offsets are limited for elliptical fitting.

Figure 1d displays the azimuthal amplitudes of R-component of PS-wave at the top of the fractured layer. It also shows the azimuthal amplitudes appears in elliptical distribution, which is similar to the behaviour of azimuthal P-wave amplitudes, except that the long axis of the ellipse is in fracture normal direction for PS-wave and in fracture strike direction for P-wave. The azimuthal amplitudes of the T-component of the PS-wave data are displayed in figure 1e and the azimuthal variations reveal zero-crossings and polarity reversals, which can also be used to infer fracture information. Figure 1f shows the interval travel-time of R-component of the PS-wave data within the fracture layer is in elliptical distribution with azimuth and the long axis of the ellipse indicates fracture normal, which is consistent with that in azimuthal P-wave analysis.
Figure 1d and 1f reveal that both the amplitudes and interval travel-time of R-component can be used to infer relative fracture density in the similar way in P-wave analysis. It also reveals that not all the R-component data of PS-wave are suitable for elliptical fitting, there are usable offset range limits just like that in azimuthal P-wave attribute analysis.

**Real data analysis**

The 3D3C land seismic data were acquired on a fractured reservoir in Shengli Oilfield with wide azimuth-offset coverage (Figure 2, where red lines are the receiver locations and the blue spots are the source locations), which aims to obtain water-oil distributions at the target layers through shear wave splitting analysis. The preliminary analysis of the PS-wave data shows good shear wave splitting information due to the well developed vertically aligned fractures in the area. Reliable fracture characterizations are extremely important for successful separation of fast and slow shear wave, which is essential for the subsequent oil-water characterization. Thus, how to obtain reliable fracture properties, especially fracture direction, is an important work that has to be done first in this oil-water discrimination attempt.

For this, we focus our effects on the use of azimuthal PS-wave data, mainly the R-component data, for the fracture characterization, then carry out combined analysis with other prior information to improve the reliability of fracture characterization results. In fact, the azimuthal anisotropy is so obvious on the PS-wave data that just a simple CCP super-gather of R-component sorted in azimuth sequence has shown significant azimuthal travel-time variations at the target reflections (Figure 3, where yellow lines indicate), revealing the good potential of using azimuthal PS-wave analysis for the fracture characterization.

In the azimuthal analysis with the R-component of PS-wave data, we use the amplitudes and interval travel-time as the main seismic attributes and apply exactly the same strategy in numerical modelling. Besides fitting azimuthal amplitudes and azimuthal interval travel-time with ellipse, we also perform independent azimuthal velocities analysis for quality control on six sub-supergathers obtained by dividing a CCP super-gather into six parts according to equally divided azimuth sections. The fracture strike direction of the final characterization results was identified as N45°E, which is in agreement with the structural alignment of the area.

After fracture characterization, we perform component rotation to transform R- and T-component data to fast shear wave (in fracture strike direction) and slow shear wave (in fracture normal direction) and figure 4 shows good fast and slow shear wave separation (in CCP gather). Figure 5 displays the corresponding fast and slow shear wave stacks (target zone) for subsequent shear wave splitting and oil-water saturations analysis (Qian, et al.,2007).

**Discussion and Conclusions**

We carry out the azimuthal seismic anisotropy analysis with PS-wave data with numerical modelling and a real 3D3C dataset. Numerical results reveal that, through the amplitudes and interval travel-time of P-wave can be used to infer fracture information through ellipse fitting, there are limits on usable offset ranges. The R-component of PS-wave can also be used for fracture characterization through elliptical fitting. The only difference is that the long axis of ellipse fitted with the amplitudes of P-wave is in fracture strike direction while the long axis of ellipse from R-component of PS-wave indicates fracture normal direction. The modelling results also show that there are limits for usable offset ranges on azimuthal PS wave data attributes analysis (e.g. for amplitude attribute, the offset-depth ratio should be within 0.6-1.0).

The fracture characterization results from the 3D3C dataset acquired on a fractured reservoir agree with that from geological and logging analysis, demonstrate the applicability of using azimuthal PS-wave data analysis for fracture characterization.

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References


![Figure 1](image-url)

**Figure 1** Numerical modelling for azimuthal P- and PS-waves.
(a) numerical model; (b) azimuthal P-wave amplitudes; (c) azimuthal P-wave interval travel-time; (d) azimuthal R-component amplitudes; (e) azimuthal T-components amplitudes; (f) azimuthal R-component interval travel-time. The Colours represent different fracture densities: the blue curve denotes fracture density of 10% and the red curve denotes the fracture density of 18%.
**Figure 2** 3D3C acquisition deployment

**Figure 3** A CCP supergather in azimuth sequence

**Figure 4** Rotation of R- and T-component to fast and slow shear wave (CCP gather).

**Figure 5** Stacks (target zone) of fast and slow shear wave.