Effects of fluid viscosity on PP and PS-waves in fractured rock
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Summary

We studied the effects of fluid viscosity, seismic frequency, angle of incidence and fracture density on the seismic anisotropy from a fluid saturated HTI medium by numerical modelling. It demonstrated the relevance of Thomsen anisotropy parameters, seismic measurements $\Delta R_{pp}$ and $\Delta R_{ps}$ with the fluid viscosity. $\Delta R_{pp}$ and $\Delta R_{ps}$ provide a potential approach to study seismic anisotropy on fracture reservoirs for fluid characterisation. However, there is a minimum angle of incidence requirement for fluid influence to be detectable. $\Delta R_{ps}$ is much more sensitive to fluid viscosity than $\Delta R_{pp}$. To observe viscosity variation from $\Delta R_{ps}$, the required angle of incidence should be larger than 20° and fracture density should be larger than 4%.
Introduction

The ability to effectively monitor fluid substitution in producing reservoirs is very important and many studies have been carried out for such a purpose. Some studies have shown the links between fluid saturated HTI media and seismic anisotropy (e.g. Chapman, 2003). A numerical and real data study indicated the potential of using fluid viscosity to characterize fluid substitution in producing fracture reservoirs (Qian, et al., 2007). However, besides viscosity, other factors such as frequency, angle of incidence, fracture density have combined effects on seismic anisotropy, thus it is very helpful to investigate the individual effect of these factors to obtain more insights into fluid characterization with viscosity. Here, we carry out a numerical analysis to study the effects of frequency, angle of incidence, fracture density and viscosity on seismic anisotropy from fluid substitution in a HTI medium.

Seismic anisotropy and measurements

The communication of fluid between fractures and equant porosity occurring as seismic wave passing by will influence medium elastic properties (Thomsen, 1995). Liu, et al. (2000) show that the normal to shear compliance ratio is related to isolated pore or fracture fluid and it is possible to estimate fluid saturation in seismic data. Chapman (2003) introduced a squirt-flow model to study frequency dependent anisotropy and established a poro-elastic equivalent medium theory involving the effects from fluid viscosity, frequency, fracture and crack density and porosity. Batzle et al. (2006) proposed a concept of fluid mobility as the ratio of permeability to viscosity to study frequency-dependent seismic velocities in the laboratory. These studies demonstrated that fluid viscosity, frequency and fracture density have influence on seismic anisotropy. However, it may be difficult to interpret it directly from seismic data.

To simplify the analysis, we use the measurements $\Delta R_{pp}$ and $\Delta R_{ps}$ to study seismic anisotropy, which represent the reflectivity difference between fracture parallel and normal directions for the P- and PS-waves, respectively (Li, 1998). In equation (1) and (2), $\delta$, $\epsilon$ and $\gamma$ are Thomsen anisotropy parameters, containing the effects from fracture density, fluid viscosity and seismic frequency; $\alpha_0$ and $\beta_0$ are average P- and S-wave velocities of the upper medium and lower (HTI) medium; $i$ and $j$ are the average propagation angles for P- and S-waves, respectively.

$$\Delta R_{pp} = \frac{1}{2} \left( \delta - 2 \epsilon + \frac{8 \beta_0^2 \gamma}{\alpha_0^2} \right) \sin^2 i$$ (1)

$$\Delta R_{ps} = \sin i \left[ \frac{\alpha_i^2}{2 \cos j} \left( \frac{\alpha_i^2}{\alpha_i^2 - \beta_0^2} (\delta - 2 \epsilon) + \frac{4 \beta_0 \gamma}{\alpha_0^2} \cos i \cos j \right) \right.$$

$$- \frac{\alpha_i^2}{\alpha_i^2 - \beta_0^2} (\delta - 2 \epsilon) \cos i \cos j - \frac{4 \beta_0^2 \gamma}{\alpha_0^2} \sin^2 i \left. \right] + (\delta - 2 \epsilon) \sin^2 i - \frac{\alpha_j^2}{\alpha_j^2 - \beta_0^2} (3 \delta - 4 \epsilon) \sin^2 i$$ (2)

Numerical analysis

The numerical model contains a porous, cracked, fluid saturated HTI layer and an overburden isotropic layer to simulate the case of a fracture reservoir under a shale layer (Figure 1). The elastic constants of the model are calculated with the method proposed by Chapman (2003), which carries the effects from fluid viscosity, fracture density, seismic frequency and angle of incidence. The Thomsen anisotropy parameters for HTI medium are then calculated from the elastic constants (Thomsen, 1986).

Figure 2a displays the distribution of Thomsen anisotropy parameters with fracture density. The frequency and viscosity

| Vp=2337m/s | Vs=1253m/s | $\rho=2.265g/cm^3$ |
| Vp=2866m/s | Vs=1648m/s | $\rho=2.326g/cm^3$ |

Figure 1: The model with a fluid saturated HTI layer in the middle.
used in the analysis is 15Hz and 20.0, respectively. It shows that $\gamma$ and $\epsilon$ increase with fracture density while $\delta$ decreases with fracture density. Figure 2b shows $\epsilon$ and $\delta$ decrease with viscosity, but $\gamma$ is insensitive to viscosity. The horizontal axis denotes the relative viscosity of the fluid to water. The fracture density is 8% and the angle of incidence is 27° for the analysis. Figure 2c displays the variations of Thomsen parameters with frequency. The changes for $\epsilon$ and $\delta$ mainly occur in the frequency range of (10 - 30 Hz), while $\gamma$ appears insensitive to frequency, which is similar to that in figure 2b.

Figure 2d shows the variations of seismic measurements $\Delta R_{pp}$ and $\Delta R_{ps}$ with fracture density. Both $\Delta R_{pp}$ and $\Delta R_{ps}$ increase with fracture, but the increase of $\Delta R_{ps}$ is much higher than that for $\Delta R_{pp}$, which indicates the S-wave is more sensitive to fracture density than the P-wave. Figure 2e shows the overall variation trend of $\Delta R_{pp}$ and $\Delta R_{ps}$ with viscosity, which is similar to that in figure 2d, but the magnitude for $\Delta R_{pp}$ and $\Delta R_{ps}$ is much smaller than that in figure 2d, which means that the P- and S-wave is less sensitive to viscosity than fracture density. Figure 2f is the distribution of $\Delta R_{pp}$ and $\Delta R_{ps}$ with frequency, which shows that around 30 Hz, there are rapid increases on $\Delta R_{pp}$ and $\Delta R_{ps}$, but the increase of $\Delta R_{ps}$ is much higher than that for $\Delta R_{pp}$. Figure 2d, 2e and 2f reveal that $\Delta R_{pp}$ and $\Delta R_{ps}$ have very similar distributions with fracture density, viscosity and frequency, but $\Delta R_{ps}$ is much more sensitive than $\Delta R_{pp}$.

Figure 3a displays the distribution of $\Delta R_{ps}$ with fracture density and angle of incidence, showing that if the angle of incidence is smaller than 10°, $\Delta R_{ps}$ is not sensitive to fracture density. It reveals that, to describe viscosity with $\Delta R_{ps}$, the angle of incidence should be larger than 20°. Figure 3c is the distribution of $\Delta R_{ps}$ with frequency and angle of incidence, showing that $\Delta R_{ps}$ is only sensitive to frequency within certain frequency band (10 – 100Hz) and the angle of incidence should be larger than 20°. Figures 3a, 3b and 3c indicate a minimum angle of incidence for $\Delta R_{ps}$ to be sensitive to frequency, fracture density and viscosity. The angle of incidence used for figure 3d, 3e and 3f is 27°.

Figure 3d is the distribution of $\Delta R_{ps}$ with viscosity and frequency. It shows that, within normal seismic frequency band (10-100Hz), $\Delta R_{ps}$ is sensitive to viscosity. Figure 3e displays $\Delta R_{ps}$ distribution with viscosity and fracture density, revealing that viscosity and fracture density have similar effects on $\Delta R_{ps}$. If fracture density is very small (less than 4%), $\Delta R_{ps}$ is not very sensitive to viscosity. Figure 3f displays $\Delta R_{ps}$ with frequency and fracture density, showing that only when frequency is larger than 10 Hz can $\Delta R_{ps}$ be sensitive to fracture density.

Conclusions

The numerical results demonstrated the relevance of Thomsen anisotropy parameters, seismic measurements $\Delta R_{pp}$ and $\Delta R_{ps}$ with the fluid viscosity, frequency, angle of incidence and fracture density. $\Delta R_{pp}$ and $\Delta R_{ps}$ provide a potential approach to study seismic anisotropy on fracture reservoirs for fluid characterisation. However, there is a minimum angle of incidence requirement for fluid influence to be detectable. $\Delta R_{ps}$ is much more sensitive to fluid viscosity than $\Delta R_{pp}$. To observe viscosity variation from $\Delta R_{ps}$, the required angle of incidence should be larger than 20° and fracture density should be larger than 4%.

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References


Figure 2: Thomsen anisotropy parameters, $\Delta R_{pp}$ and $\Delta R_{ps}$ with fracture density (%), viscosity and frequency (log Hz).
ΔR_{ps} change with fracture density and incidence angle. frequency = 15Hz; viscosity = 20.

ΔR_{ps} change with viscosity and incidence angle. fracture density = 10%; frequency = 15Hz.

ΔR_{ps} change with frequency and incidence angle. fracture density = 10%; viscosity = 20.

ΔR_{ps} change with viscosity and frequency. fracture density = 10%; incidence angle = 27°.

ΔR_{ps} change with viscosity and fracture density. frequency = 15 Hz, incidence angle = 27°.

ΔR_{ps} change with frequency and fracture density. viscosity = 20; incidence angle = 27°.

**Figure 3**: Seismic measurement ΔR_{ps} changes with, (a) fracture density and angle of incidence, (b) viscosity and angle of incidence, (c) frequency and angle of incidence, (d) viscosity and frequency, (e) viscosity and fracture density, (f) frequency and fracture density.