The Reflectivity Response of Multiple Fractures and its Implications for Azimuthal AVO Inversion

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Summary

The presence of fractures in the subsurface and their tendency to provide natural pathways for hydrocarbon flow make them an important target in the exploration and exploitation of oil and gas reservoirs. The present study aims at understanding how fractures affect seismic wave propagation and azimuthal AVO inversion results. The work was done following three main steps. First, in order to gain understanding of the effect of fractures on the elastic properties of rock, we modelled two-layered media containing multiple sets of fractures characterized by their dip, azimuth, intensity and linear slip parameters and calculated the stiffness matrix of the effective media following Sayers and Kachanov (1995). Knowing the elastic parameters of the media, the next step was to compute the azimuthal reflectivity response using a linear approximation (Pšencík and Martins, 2001) and generated synthetic gathers for the different fractured media. The last step was to test the azimuthal AVO inversion developed by Downton and Roure (2010) with the synthetic seismic gathers created. The inversion algorithm currently assumes HTI media (a single set of vertical fractures per layer) and uses an approximation to compute the reflectivity. Thus, inverting the above synthetic gathers enabled us to understand whether the inversion yields reasonable results with current approximations and assumptions.

Introduction

Knowledge of the orientation and density of fractures is required to optimize production from naturally fractured reservoirs. Indeed, areas of high fracture density may represent zones of high permeability and it is important to be able to target such locations for infill drilling. Besides, fractures often show preferred orientations which may result in significant permeability anisotropy in the reservoir and it is important for optimum drainage that the separation of producers should be more closely spaced along the direction of minimum permeability than along the direction of maximum permeability (Sayers, 2009). Amplitude variations with offset (AVO) and azimuth are sensitive to the presence of fractures. Hence, azimuthal AVO inversion has become a useful tool to predict fractures. However, current models used to invert the seismic response often make simplified assumptions that prevent fractured reservoirs from being characterized correctly. For example, many models assume a single set of perfectly aligned fractures, whereas most reservoirs contain several fracture sets with variable orientation. This work aimed at addressing some of these issues. We proceeded in three steps. The first one involved studying various rock physics models in order to model the impact of multiple fractures on the elastic parameters of an isotropic medium. Then, we calculated the PP-reflectivity response at an interface separating two anisotropic media by using an approximation. Finally, we tested the azimuthal AVO inversion developed by Downton and Roure (2010) to predict fractures to check if it still yields reasonable results with more realistic input, i.e. with data corresponding to more complex fracture configurations than the assumed parallel vertical fractures.

Reflectivity computation

The stiffness matrix expresses the elastic parameters of a given medium and in the isotropic case can easily be computed knowing the P- and S- waves velocities and the density. The linear slip deformation (LSD) theory (Schoenberg, 1980) allows us to include the effect of fractures by applying a correction to the compliance matrix of the background which, we will assume, is isotropic or transversely isotropic. Schoenberg and Sayers (1995) expresses the HTI stiffness matrix in terms of isotropic parameters λ and μ, and the normal and tangential weaknesses Δ_N and Δ_T. These weakness parameters are dimensionless and describe how fractures weaken a background isotropic rock.

Sayers and Kachanov (1995) extended the LSD theory to rocks containing multiple sets of fractures, each of them having a given orientation. Assuming that cracks are planar and neglecting interactions between fractures, they expressed the excess compliance Δs_{ijkl} due to cracks in terms of a second-rank and a fourth-rank tensors. Using Voigt recipe and introducing factors 2 and 4 (Nye, 1985), we can rewrite Δs_{ijkl} as a matrix, which will lead to the stiffness matrix of the effective medium.

In order to understand the impact of fractures on azimuthal AVO, it is necessary to evaluate the reflectivity of an interface as a function of azimuth when the media involved are not isotropic. Pšencík and Martins (2001) derived a formula for the PP-wave reflection coefficient for weak contrast interfaces separating two weakly but arbitrarily anisotropic media, meaning that the symmetry axis is not necessarily parallel to the reflector. This is of high interest since it will enable us to model dipping fractures. According to their study, the PP-reflection coefficient can be expressed as a function of the PP-reflection coefficient for isotropic media and a perturbation due to weak anisotropy.

Modelling and inversion

We modelled two-layered media containing multiple sets of fractures with different azimuths and dips per layer. We considered fractures embedded in an isotropic background defined by the P-wave velocity V_{P0}, S-wave velocity V_{S0} and the density ρ_0. Each set of fractures was then characterized by:

- the parameters related to the dip δ_{dip} (measured anti-clockwise from the vertical x_3-axis) and the orientation of the normal to the fractures Φ_{sym} (measured anti-clockwise from the x1-axis),
- the linear slip parameters, i.e. the tangential weakness Δ_T and the compliance ratio $B = B_N/B_T$ of the fractures.
- the crack density η_{crack} which is defined as the number of fractures per unit length.

We studied various models in order to see the impact fractures have on elastic parameters and reflectivity. Both models presented in figure 1 contain two layers: the upper layer (layer 1) is isotropic and the lower layer (layer 2) is the fractured medium.

Parameters	Layer 1	Model 1: Layer 2	Model 2: Layer 2
V_{P0} (m/s)	4000	4400	4400
V_{S0} (m/s)	2000	2200	2200
ρ_0 (kg/m^3)	2500	2500	2500
δ_{dip} (°)		δ_{dip}	[0;0]
Φ_{sym} (°)		0	[$-\Phi_1$; $+\Phi_1$]
Δ_T		0.1	[0.1;0.1]
B		0.5	[0.5;0.5]
η_{crack} (m^{-1})		1	[0.5;0.5]

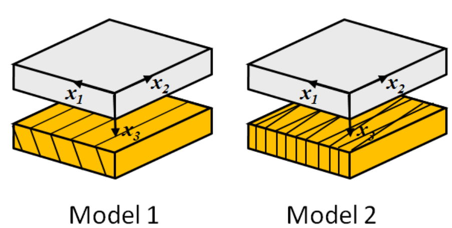

Figure 1: Models and parameters used to understand the impact of fractures on reflectivity.

Naturally occurring fractures are often dipping. Hence, it is of high interest to be able to model non-vertical fractures. The first model was used to study the impact of fractures with various dips δ_{dip} ranging from 0° to 45°. Note that when δ_{dip} =0°, the fractures are vertical which leads to a HTI medium. Figure 2 shows the reflection coefficients as a function of azimuth and angle of incidence obtained for δ_{dip} =0°, 15°, 30° and 45° (left to right). We notice an increase in the azimuthal variation of the reflectivity response as the dip becomes larger.

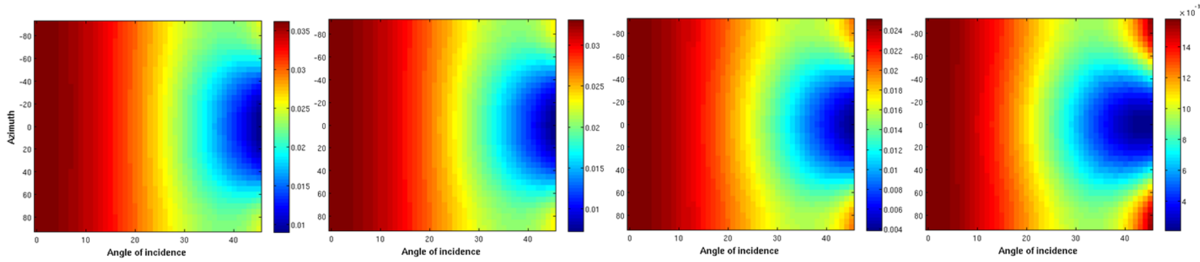

Figure 2: Impact of the dip on the reflectivity coefficients. Left to right, δ_{dip} =0°, 15°, 30° and 45°.

We then modelled two sets of identical vertical fractures. The goal was to determine if media containing two sets of identical fractures were comparable to HTI media containing a single set of vertical fractures when the angle $\Delta\Phi$ between both sets was small ($\Delta\Phi=2\Phi_1$ in model 2). As we see on figure 3, when both sets of fractures are separated by an angle inferior to 30°, the reflectivity response of the orthorhombic medium is similar to the one of an equivalent HTI medium. Then, we notice a decrease in the azimuthal variation of the reflectivity response when we increase the angle separating both sets of fractures. Besides, we can distinguish on figure 3 (right) the influence of each set of fractures separately.

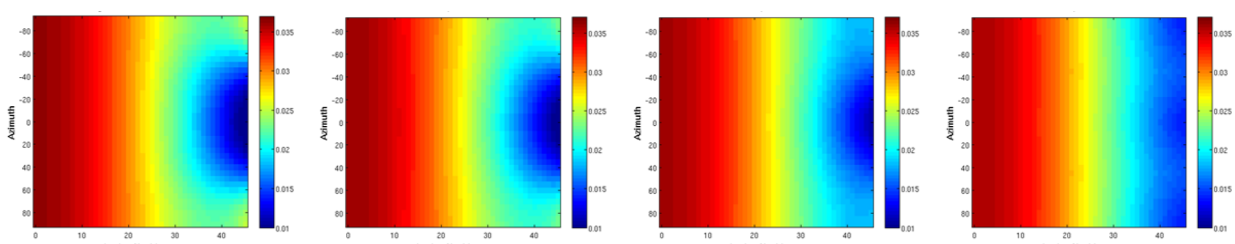

Figure 3: Reflectivity coefficients of orthorhombic media containing two sets of identical fractures.
Left to right, Φ_1 = 0°, 15°, 30° and 45°, corresponding to $\Delta\Phi$=0°, 30°, 60° and 90°.

Once the reflectivity response was known for a given medium, we did some convolutional modelling (using an 80Hz Ricker wavelet) to create the synthetic data which enabled us to test the azimuthal AVO inversion algorithm. The 1D models described in figure 1 were duplicated along the x_1 and x_2 axes in order to obtain 3D seismic cubes for various angle-azimuthal values.

Figure 4 shows the Δ_T and Δ_N estimates displayed as probability distributions for model 1 with δ_{dip} = 0°, 5°, 10° and 15° (left to right). The ideal solution, which corresponds to the Δ_T and Δ_N values used to create the input synthetic data, is highlighted by the red lines. First, we notice that for the inverted HTI medium (left), the Δ_T and Δ_N estimates match quite well the ideal solution. As the dip increases, the Δ_T and Δ_N values slowly drift towards an overestimation. However, even for δ_{dip} =15°, the bias introduced is still reasonable considering the size of the solution space.

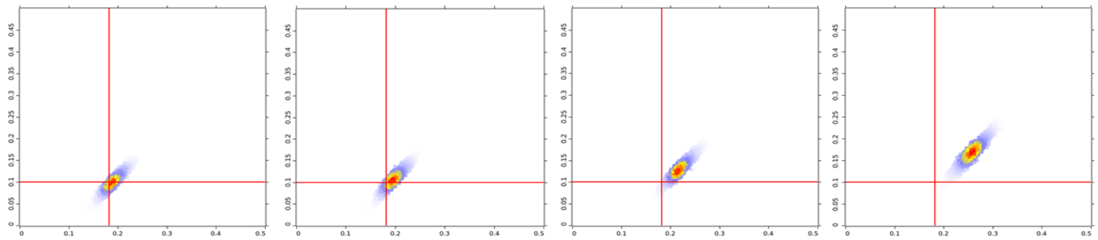

Figure 4: Inversion results for dipping fractures. Left to right, δ_{dip} =0°, 5°, 10° and 15°.

The results of the inversion on model 2 are shown in figure 5 for $\Delta\Phi$ = 0°, 10°, 20° and 30° (left to right). We notice for each case, even for fractures separated by an angle of 30°, that there is a good match with the ideal solution.

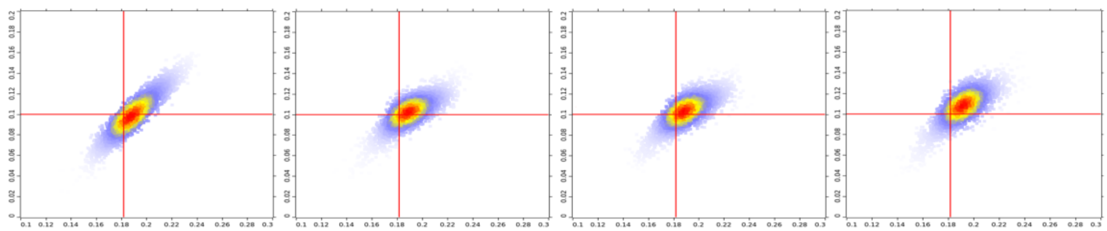

Figure 5: Inversion results for orthorhombic media containing two sets of identical fractures.
Left to right, $\Delta\Phi$=0°, 10°, 20° and 30°.

Conclusions

We developed some reflectivity modelling for isotropic media containing multiple sets of fractures with various dips and azimuths. This reflectivity modelling uses Sayers and Kachanov (1995) theory to compute the elastic parameters of fractured media, and Pšencík and Martins (2001) approximation to calculate the PP-reflectivity response at an interface separating two anisotropic media. After studying the reflectivity response of various fractured media, we did some convolutional modelling in order to generate synthetic datasets. Finally, the synthetic data created were inverted in order to test the azimuthal AVO inversion developed by Downton and Roure (2010) to predict fractures. We saw that, despite restrictive assumptions, the inversion still yields reasonable results for media containing two sets of identical fractures separated by a small angle and it only introduces a small bias in the case of dipping fractures.

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