Synthetic modelling study of the effect of attenuation anisotropy in fractured media

Ekanem, A. M.¹, ², Li, X-Y.¹, ², Chapman, M.¹, ² and Main, I.G.¹

¹ School of Geosciences, University of Edinburgh, West Mains Road, Edinburgh, EH9 3JW, UK
² British Geological Survey, Murchison House, West Mains Road, Edinburgh, EH9 3LA, UK

Summary

We present the results of a synthetic modelling study of the effect of attenuation anisotropy in fractured media. Our theoretical model is made up of one anisotropic and three isotropic horizontal layers. The anisotropic layer consists of a porous fluid-saturated material with aligned vertical fractures, and squirt flow between the pores in the matrix is taken into consideration. We used the spectral ratio method to compute the seismic quality factor, Q, from the synthetic data in four azimuthal directions relative to the fracture strike. The results of our measurement indicate that attenuation increases with incidence angle and azimuth away from the fracture strike. Azimuthal variations in the induced attenuation are elliptical and the fracture orientations obtained from the axes of the ellipse are consistent with the theoretical model. We conclude that these effects, if observed in field data, could be used to determine fracture orientations in the subsurface to supplement the use of other seismic attributes.
Introduction

A suite of aligned fractures are known to cause seismic attenuation, in which geoscientists have taken an increasing interest over recent years. Attenuation anisotropy has been observed in both field and laboratory data (e.g. Rathore et al. 1995; Luo et al. 2006; Maultzsch et al. 2007; etc) and has been linked to fracture properties. As attenuation anisotropy continues to gain popularity as a useful exploration tool, a concerted effort is needed to get more insight of its characteristics, using theoretical models to aid our understanding of the underlying physics.

In this paper, we have carried out a synthetic modeling study of P-wave attenuation anisotropy in fractured media. Our theoretical model consists of one anisotropic and three isotropic horizontal layers. The elastic parameters of the material of the anisotropic layer were computed using the dynamic equivalent-medium theory of Chapman (2003) and we used the classical spectral ratio method to compute the induced attenuation for selected offsets at four azimuths relative to the fracture strike direction. Our results indicate that the azimuthal variations of attenuation are approximately elliptical and the inferred fracture orientations are consistent with the theoretical model.

Theoretical model and experimental set-up

The theoretical model is made up of one anisotropic and three isotropic horizontal layers. The anisotropic layer consists of a porous fluid-saturated material with aligned vertical fractures, and squirt flow between the pores in the matrix is taken into consideration. The elastic properties of the material are computed using the poroelastic model of Chapman (2003) which considers the pore space of the rock to consist of spherical pores and circular cracks of small aspect ratio. The pressure difference generated when a seismic wave propagates through the medium causes fluid exchange between the fractures and the surrounding pore space, resulting in attenuation and dispersion. Chapman’s (2003) poroelastic model predicts anisotropic velocity dispersion and attenuation in the seismic frequency range, with attenuation increasing with polar angle and azimuth away from the fracture strike. Details of the theoretical model parameters are given in Table 1. The third layer constitutes the anisotropic layer.

<table>
<thead>
<tr>
<th>Layer</th>
<th>v_p (m/s)</th>
<th>v_s (m/s)</th>
<th>( \rho ) (Kg/m^3)</th>
<th>Thickness (m)</th>
</tr>
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<tr>
<td>1</td>
<td>1500</td>
<td>1000</td>
<td>1000</td>
<td>400</td>
</tr>
<tr>
<td>2</td>
<td>2314</td>
<td>1100</td>
<td>1150</td>
<td>600</td>
</tr>
<tr>
<td>3</td>
<td>2610</td>
<td>1300</td>
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<td>600</td>
</tr>
<tr>
<td>4</td>
<td>3100</td>
<td>1800</td>
<td>2200</td>
<td>Half space</td>
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<table>
<thead>
<tr>
<th>Fracture model parameters</th>
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<tbody>
<tr>
<td>Porosity 0.08</td>
</tr>
<tr>
<td>Crack density 0</td>
</tr>
<tr>
<td>Fracture density 0.1</td>
</tr>
<tr>
<td>Fracture radius 10cm</td>
</tr>
<tr>
<td>Fluid bulk modulus 2.0Gpa</td>
</tr>
<tr>
<td>Relaxation time 50Hz</td>
</tr>
<tr>
<td>tau_0</td>
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</table>

The synthetic data were computed from the theoretical model using the ‘Aniseis’ software (Taylor 2001) which makes use of the reflectivity method, at four azimuths 0°, 45°, 60° and 90° relative to the fracture strike direction which corresponds to 0° azimuth. A Ricker wavelet with a centre frequency of 25Hz and a start time of 100ms was used as the source wavelet. The source is an explosive source and was placed on the surface of the model. 21 geophones were also placed on the surface of the model, at a regular spacing of 200m, and a source - receiver spacing of 200m was maintained. Data were recorded with a sampling interval of 1ms and a total time of 3s. Sample synthetic data are given in Figure 1.
Q estimation

We used the spectral ratio method (e.g. Tonn, 1991) to estimate the seismic quality factor, Q from the synthetic data for selected offsets. In each gather, the first trace from the top model reflection was used as the reference trace for comparison of the spectral ratios. We performed a simple least square regression of the Log of the Power Spectral Ratios (LPSR) against frequency according to the equation:

\[
\ln\left(\frac{P_2(f)}{P_1(f)}\right) = 2\ln(RG) - 2\pi\left(t_t - t_{ref}\right)/Q
\]

where \(P_2(f)\) is the spectral power of the target reflection (top or bottom fractured layer) and \(P_1(f)\) is the spectral power of the reference trace, \(f\) is the frequency, \(R\) is the reflectivity term, \(G\) is the geometrical spreading term, \(t_t\) is the travel-time of the target reflection, \(t_{ref}\) is travel-time of the reference event and \(Q\) is the quality factor down to the reflector.

![Figure 1: Sample synthetic gathers. (a) 0° azimuth (b) 90° azimuth. Red and green arrows indicate top and bottom fractured layer reflections respectively; the pink circle highlights the converted wave.](image)

We used a constant FFT time window of 140ms to compute the power spectra, and a bandwidth of 20-90Hz where the spectral ratio plots were stable (Figure 2) for the regression. For a given offset, we computed Q down to the reflector from the slope, \(p\) of the least square regression given by:

\[
p = 2\pi\left(t_{ref} - t_{t}\right)/Q
\]

With the two pair of Q values computed for the top and bottom fractured layer, we used the layer-stripping method of Dasgupta and Clark (1998) to compute the interval Q value in the fractured layer using the equation:

\[
Q = \frac{t_t - t_{n-1}}{t_t/Q_n - t_{n-1}/Q_{n-1}}
\]

where \(Q_n\) and \(Q_{n-1}\) are the quality factors for the reflectors at the two-way traveltimes of \(t_t\) and \(t_{n-1}\) corresponding to the top and bottom of the fractured layer respectively.

Results

The results of our study show that attenuation varies both with incidence angle and azimuth relative the fracture strike direction. Attenuation increases with incidence angle and also away from the fracture strike direction with maximum attenuation normal to the fractures (Figure 3a). Azimuthal
variations in the attenuation are elliptical to a good approximation (Figure 3b). However, the results show that a minimum of 400m offset (8.4° incidence angle) is required to reveal the azimuthal variations. The major axis of the Q - ellipse corresponds to the fracture strike where attenuation is a minimum, while the minor axis corresponds to the fracture normal where attenuation is a maximum.

Figure 2: Log Power Spectral Ratio (LPSR) against frequency. (a) Top fracture layer reflection (b) bottom fractured layer reflection. Boxes indicate the respective offsets. Plots are stable within the frequency bandwidth of 20 to 90 Hz.

The attenuation anisotropy also obeys a cosine fit of the form (Maultzsch et al. 2007):

$$\Delta Q^{-1} = C1 + C2 \cos[2(\phi - \phi_o)]$$

(4)

where $C1$ is an arbitrary constant, $C2$ is the magnitude of azimuthal variation, $\phi$ is the azimuthal angle and $\phi_o$ is the fracture normal direction at which attenuation is maximum. Figure 4 shows the cosine fits to the Q results for selected offsets. The azimuth of maximum attenuation from the fits is 90° which corresponds to the fracture normal. The magnitude of the attenuation anisotropy increases with incidence angle (offset).

Figure 3: Attenuation results. (a) Q profile with incidence angles. Attenuation increases with incident angles. There is no significant change of attenuation with incidence angle at the fracture strike azimuth. (b) Q anisotropy ellipse. Azimuthal variations in Q are elliptical and the fracture orientations are derived from the axes of the ellipses.

Conclusion

The results of our synthetic modelling study show that attenuation increases with incidence (polar) angle and also increases away from the fracture strike direction, which is consistent with the predictions of Chapman’s model (2003) and the results of similar studies of Maultzsch et al (2007) in
a walkaway VSP setting. Azimuthal variations in the induced attenuation are elliptical and the fracture orientations are quite easily obtained from the axes of the ellipse. We conclude that if attenuation anisotropy is observed in field data, it could be a potential tool to determine fracture orientations in the subsurface to supplement the use of amplitudes, travel time, velocity and AVO gradient attributes.

Figure 4: Cosine fits of estimated 1/Q values against azimuth for given offsets. Degree of anisotropy increases with offset (incidence angle). No azimuthal variations are observed at 200m offset (4.2° incidence angle).

Acknowledgement

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References