P-wave attenuation anisotropy in fractured media: results from a laboratory ‘scale-model’

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Summary

We used a laboratory scale model to study the effects aligned fractures might have on seismic wave propagation at a larger scale in real Earth imaging. Our main objective was to investigate the effects of aligned fractures on seismic wave amplitude through the estimation of fracture–induced attenuation and relating these effects to the fracture properties. The physical model comprised two fracture models constructed from a mixture of epoxy resin and silicon rubber and designed to simulate two sets of intersecting fractures. Two-dimensional survey data were acquired using the pulse-transmission method in three principal directions with the model submerged in a water tank. The Quality Versus Offset (QVO) method, an extension of the classical spectral ratio method for determining attenuation, was used to estimate the quality factor from the NMO-corrected CMP gathers. The results of the study reveal attenuation anisotropy in the physical modelling data sets. Attenuation was observed to increase systematically away from the fracture strike, with a maximum at the fracture normal. Azimuthal variations in the fracture-induced attenuation were elliptical to a good approximation, enabling fracture orientations to be obtained quite accurately from the axes of the ellipse. We concluded that attenuation anisotropy may be used in fracture characterization to complement the use of travel-times, velocity, amplitude and AVO gradient attributes.
Introduction

There has been an increasing use of seismic anisotropy to detect natural fractures in recent times. Although attenuation anisotropy has been observed in laboratory and field data (e.g. Rathore et al. 1995; Luo et al. 2006; Maultzsch et al. 2007; etc), its application in seismic exploration still remains a challenging topic as the mechanisms causing it and its measurement are still poorly understood. Thus, a detailed study of attenuation anisotropy through seismic physical modelling could add more understanding to improve fracture detection to complement the use of travel-times, velocity, amplitude and AVO gradient attributes.

In this paper, we have carried out a seismic physical modelling study of P-wave attenuation anisotropy in fractured media. The physical model is made up of two horizontal layers. The second layer has inclusions of thin penny-shaped chips, as in Wei et al. 2007 to simulate two intersecting fracture models of different fracture densities. 2D data were acquired with the physical model soaked in a water tank in three principal directions using the pulse-transmission method. Our main aim is to investigate the effects of attenuation anisotropy caused by these aligned fractures and see if we could link it to the fracture parameters. We used the QVO method introduced by Dasgupta and Clark (1998) to estimate the quality factor from the pre-processed CMP data. The results of our measurements show that maximum attenuation occurs in the direction perpendicular to the fracture strike and minimum attenuation in the direction parallel to the fracture strike. The attenuation anisotropy observed in the data is described approximately by the ellipse and the major axis of the Q ellipse indicates the fracture strike while the minor axis indicates the fracture normal.

Construction of physical model

The physical model is constructed from two horizontal layers (Figure 1). The first layer is made from epoxy resin and is isotropic with a thickness of 31.6mm, P-wave velocity of 2314m/s, S-wave velocity of 1100m/s and density of 1.15g/cm³. The second layer is made from a mixture of epoxy resin and silicon rubber and has a thickness of 59.1mm, P-wave velocity of 2610m/s, S-wave velocity of 1183m/s and density of 1.175g/cm³. Thin low velocity penny-shaped chips made from a mixture of epoxy resin and silicon rubber are introduced into the isotropic background of the second layer following Hudson’s (1981) equivalent medium theory to simulate two sets of intersecting fracture models A and B (Figure 2b). The penny-shaped chips all have the same diameter of 3mm and thickness of 0.128mm. The two fracture models A and B are made of 144 and 18 layers of epoxy resin respectively. Once a layer is laid, 120 thin round chips are randomly embedded into the layer and another layer is added on the top. The whole process is repeated until the desired number of layers is achieved. The fracture density of each fracture model is given by:

$$\chi = N\alpha^3V^{-1} \quad (1)$$

where N is the number of chips in the base material, V is the volume of the base material model and ‘a’ is the radius of each chip. Model A has a fracture density of 0.0635 while that of model B is 0.057.

Experimental set–up / data acquisition

The experimental set-up for the data acquisition is illustrated in Figure 2(a). The physical model was soaked in a water tank and the water depth to the top of the model is 80mm. 2-D data were acquired in three principal directions; the SN and WE and NWSE directions respectively as indicated by the blue-arrowed lines in Figure 2(b). The modelling system comprises an ultrasonic pulse source and a receiver system, an analogue/digital converter and
a motor driven positioning system with a precision of 0.1mm. The source and receiver were moved along the water surface. A total of 230 shots were made with a spacing of 2mm and receiver interval of 2mm at 16mm minimum offset. The ultrasonic pulse source has a centre frequency of 230KHz and a bandwidth of 130 – 330KHz.

The P-wave generated in the experiment has an approximate wavelength of 11mm which is greater than the fracture diameter (3mm), satisfying the long wavelength assumption of the equivalent wave theories of wave propagation in fractured media.

Data Processing

The data was processed so as to preserve all amplitude information needed for the determination of the seismic quality factor Q. The major processing sequences applied to the data are: raw data loading into the software, geometry configuration, common depth point (CDP) sorting, trace muting, velocity analysis and NMO correction. For easy identification of events and picking of the traveltimes to the target layers, it was necessary to also include stacking in the processing flow even though the QVO method does not work on stacked sections.

Q estimation

Existing methods of estimating attenuation from seismic data include the spectral ratio method, the amplitude decay method, the rise-time method, the centroid frequency-shift method, the wavelet modelling, the Pulse broadening method and the Inversion methods (Tonn, 1991). Here, we used the QVO method introduced by Dasgupta and Clark (1998) to estimate the quality factor Q from the NMO corrected CMP gathers. An offset range of 160 – 860m was selected for both the SN and WE lines due to issues of continuity of top fracture layer reflections while 160-1340m offset range was selected for the NWSE data, thus satisfying the small-spread approximation of the QVO method. The first trace from the top model reflection was selected as the reference trace for comparison of the spectral ratios. We
computed the spectral power ratios of the top and bottom fractured-layer reflections $P_1(f)$ on a trace-by-trace basis and divided it by that of the reference trace $P_0(f)$.

These ratios are related by following equation:

$$\ln \left( \frac{P_1(f)}{P_0(f)} \right) = 2\ln(RG) - 2\pi f(t_o - t_{ref}) / Q$$

where $f$ is frequency, $R$ is the reflectivity term, $G$ is the geometrical spreading term, $t_o$ is the zero offset travel-time of target reflection, $t_{ref}$ is the zero-offset travel-time of reference event and $Q$ is the quality factor down to the reflector.

Figure 3: Sample CDP gathers (SN line). Arrows indicate reflections from interfaces shown in Figure 2. (a) Sample gather before NMO correction (b) Sample gather after NMO correction.

A simple least-square regression, which acknowledges error bounds in slopes and intercepts (Dasgupta and Clark, 1998) of the spectral ratios against frequency, gives the slope, $p$ as:

$$p = 2\pi (t_{ref} - t_o) / Q$$

The QVO method envisages that the spectral ratio slope varies linearly with the square of offsets since the travel-times are hyperbolic. Hence, we carried out a second least-square regression of the ratio slopes against the square of the offsets to get the zero-offset slope from where the interval $Q_i$ value down to the reflector was estimated using the equation (Dasgupta and Clark, 1998);

$$Q_i = \frac{t_o}{Q_n} \left[ t_o - t_{n-1} / Q_{n-1} \right]$$

where $Q_n$ and $Q_{n-1}$ are the quality factors for the reflectors at two-way traveltimes of $t_o$ and $t_{n-1}$ respectively.

Results

The results of our analysis show that high $Q$ values are obtained at the ends of the survey lines where there are no fractures (Figure 4).
The Q values decreases to a minimum at the centre of the fracture model A. Interval Q values of 11.58 ± 2.1 (parallel to strike – model A), 7.26 ± 2.92 perpendicular to strike – model A), 8.68 ± 2.08 (60.8° to strike – model B) and 8.81 ± 0.89 (135° to strike – model A) were obtained.

Conclusions

We have carried out a physical modelling study of attenuation anisotropy in fractured media. The results of the study show that attenuation increases away from the fracture strike towards the fracture normal and is maximum normal to the fractures. The attenuation anisotropy is described approximately by the ellipse and the fracture parameters can be obtained from the axis of the ellipse. The major axis of the Q ellipse corresponds to the fracture strike while the minor axis corresponds to the fracture normal. This information can be used to characterise fractures to supplement the use of amplitudes, travel time, velocity and AVO gradient attributes.

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References


